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Sub-clinical respiratory infection identified on farms by monitoring weight changes of pigs with the Weight-Detect instrument

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Abstract. The essential task of growth rate monitoring of pigs is usually undertaken on farms using electronic scales, but new technologies are now available to continuously monitor the weight of pigs. One of these systems (Weight-Detect, WD, PLF Agritech, Brisbane, Australia) has been introduced on a commercial pig farm in Spain as part of the EU funded aWISH project to (1) assess the applicability of the technology and (2) use this information to assess the general welfare status of pigs. The WD unit was installed in early 2024 and manual weight recordings were undertaken periodically using an electronic scale to validate the WD system. In terms of absolute values, the manual measurements indicated that the WD system was able to predict the average pen weight of the pigs with 1.7% (2.0 kg) precision. More importantly, this case study demonstrated that the WD unit was able to detect weight reduction in pigs six days before the clinical signs of a respiratory disease infection were noticed. According to the WD measurements the study pigs achieved an average daily gain (ADG) of 882 g d^{-1} between the 20/03/24 and 16/04/2024. However, between the 17/4/2024 and 30/04/2024 their ADG dropped dramatically to 286 g d^{-1}. The animals were diagnosed with respiratory disease on the 22/04/24, six days after the dramatic reduction in ADG was recorded by the WD system. This period of ADG stagnation has caused an approximate 14-day delay in reaching the desired slaughter weight, (approx. 130 kg), potentially creating significant financial losses for the producer. After the 1/05/24 pigs recovered and achieved an ADG of 645 g d^{-1} until their last recorded weighing day on the 20/5/24. These results highlight the WD system's ability to alert livestock managers about impending health problems before clinical signs appear, so appropriate mitigation measures can be implemented to reduce the negative impacts on welfare and production performance.

Key words: ICT tools, image analysis, profitability, smart technologies, weight detection.

INTRODUCTION

Regular monitoring of pig growth rates is a common practice in the farming industry to ensure operational efficiency (Emmans & Kyriazakis, 1997; Banhazi, 2013). Key indicators such as Average Daily Gains (ADGs), which measure the weight increase over specific time periods, are essential for assessing growth efficiency. Thus, regular monitoring of both average pen weights (APWs) and ADGs is a crucial responsibility for farm managers (Hicks et al., 1998; Losinger, 1998; Honeyman & Kent, 2001). Traditionally, this has involved periodic and manual weight checks using electronic scales (Van der Stuyft et al., 1991; Banhazi et al., 2022c). On most farms, pigs undergo spot-check weighing just a few times during their growth phase to evaluate their performance (Korthals, 2001; Kollis et al., 2007; Banhazi et al., 2022c). However, more frequent measurements of APWs and ADGs are recommended for identifying inefficiency periods sooner (Banhazi et al., 2012). Studies indicate that occasional spot-checks can overlook short-term inefficiencies on commercial farms, which can significantly degrade overall growth efficiency if not promptly rectified (O'Connell et al., 2004; Banhazi & Black, 2009; Willis et al., 2016; Black & Banhazi, 2022).

Emerging Precision Livestock Farming (PLF) technologies present solutions for automated, continuous weight monitoring of pigs in pens, aiming to identify and mitigate inefficiency periods (Brandl & Jorgensen, 1996; Schofield et al., 1999; Wang et al., 2006; Parsons et al., 2007; Banhazi et al., 2011). These advanced PLF tools enable livestock managers to automatically gather weight data, analyse it, and make informed management decisions based on the findings (Banhazi et al., 2022b), while transforming commercial livestock production facilities into virtual research labs (Banhazi & Black, 2009). PLF AgriTech Pty Ltd. has also developed a sophisticated weight prediction technology (Weight-Detect, WD, PLF AgriTech, Brisbane, QLD) and this innovation has the potential to drastically cut production costs on pig farms (Black & Banhazi, 2013; Black et al., 2016). However, the full range of benefits from these technologies remains unclear, particularly in terms of their application for health and welfare monitoring. To explore these possibilities, a WD system has been installed on a commercial pig farm in Spain as part of the EU-funded aWISH project (HEurope grant 101060818). The project's objectives included assessing the technology's feasibility and utility for monitoring pig health and welfare. Ultimately, this study aimed to quantify the advantages of utilizing weight monitoring tools specifically and PLF technologies generally on commercial farms.

MATERIALS AND METHODS

Equipment installation on the study farm

The pen monitored was located in traditional grower-finisher building in the northern part of Spain with automatically controlled natural ventilation system installed. All experimental pigs were fed pelleted diet and were kept on fully slatted floors. After the study pen was selected, the WD equipment was installed in early 2024 at approximately 2.0 m height. Fig. 1 shows the installation location of the WD system in the study pen. Corresponding manual weighing procedures were undertaken on the farms in the same pen at varying intervals based on normal on-farm management procedures using an electronic scale (WA08, Meier-Brakenberg, Extertal, Germany). Nine pigs were housed in the study pen and the APWs were predicted daily. ADG values were calculated for a specific period by subdividing the weight gain (difference between starting and finishing weights) by the number of days of a given period. Standard farm reports were emailed to the farm manager weekly by PLF Agritech staff.

Figure 1. The WD camera installed above the resting area in the pen on a commercial farm in Spain.

Description of WD instrument

The functionality of the WD instruments has been described previously, so only a brief description will be given here (Banhazi et al., 2011, 2022b). The WD instruments utilize an off-the-shelf 3D camera (Basler ToF Camera, Ahrensburg, Germany) with a 30-fps frame rate and a maximum and minimum depth of 6 m and 0.5 m, respectively. The processing component of the WD (Fitlet 2, Compulab, Yokneam Illit) system operates via two processes: one acquires depth images (after detecting 'pig shapes'), while the other handles the processing of these images in real-time. Weight prediction is achieved by analysing and extracting features and measurements from the captured images, generating corresponding weight estimates (Banhazi & Dunn, 2016; Banhazi et al., 2022b).

Figure 2. The data processing and communication unit of the WD system before deployment.

This prediction process is conducted in real-time using the Automated Data Analysis and Management System (ADAMS), a secure database operated by PLF Agritech Pty. Ltd. (PLFAg) and maintained in the Amazon cloud. ADAMS facilitates automatic analysis of collected data and the generation of periodic reports, which is then emailed to users. The system has been patented in Australia, USA and in Europe (Banhazi & Dunn, 2016). Fig. 2 shows the data processing component of the WD system.

Data management and analysis

Automated reports were emailed to the producer in a PDF format reporting on APW and ADG information related to the study pen. In the reports and in this study, descriptive statistics have been used to generate the average, maximum, minimum values and other important parameters. The predicted and measured APWs were also compared using descriptive statistical methods in this study. As this study was an observational study (and not a classic treatment vs. control experiment), no additional statistical analysis was undertaken.

RESULTS AND DISCUSSION

The descriptive statistics associated with the dataset is displayed in Table 1. The average errors of all measurements were 2.0 kg or 1.7%. Fig. 3. illustrates the difference between APW data captured by the WD instrument and the data captured by manually operated weight scale during different growth periods between 20/03/24 and 20/05/24 on the Spanish farm. The APW data predicted by the WD instrument and corresponding manually collected data (gold standard) are shown in Fig. 4.

Table 1. Descriptive statistics of weight measurements obtained throughout the study

Measurement days (date)	27/03/2024	15/04/2024	30/04/2024	16/5/24
Max weight in pen (kg)	106.0	126.0	140.0	157.8
Min. weight in pen (kg)	75.0	98.2	104.0	112.2
Range (kg)	31.0	27.8	36.0	45.6
Measured APW (kg)	93.3	110.7	118.7	130.7
Predicted APW (kg)	94.3	111.3	115.9	127.2
difference (kg)	1.0	0.6	2.8	3.5
difference (%)	1.1	0.5	2.4	2.7

In terms of absolute values, the four (4) manual measurements indicated that the WD system was able to predict the APWs of the pigs with 1.1% (1.0 kg), 0.5% (0.6 kg), 2.4% (2.8 kg) and 2.7% (3.5 kg) precision respectively, despite the fact that range (spread) of the weight measurements within the groups were 31.0 kg, 27.8 kg, 36.0 kg and 45.6 kg, respectively. The pigs were uneven in this study pen which made weight prediction challenging as explained previously (Banhazi et al., 2022b). Despite the unfavourable experimental conditions, the WD unit performed with less than 3% error margin. However, it is recognised that generating realistic expectations about the expected precision of WD units is paramount (Artmann, 1999; Kopler et al., 2023) when communicating with end users. Many companies tend to overstate the precision and capabilities of such image-analysis based weighing systems, which can lead the development of unrealistic expectation in end-users. It is important to clearly communicate the reasons for any imprecision to users. Factors such as the timing of urine and faecal release, as well as feed and water intake, can cause fluctuations in body weight, making certain differences in weight acceptable and indeed expected (Liu et al., 2023). This study also demonstrated a clear correlation between increased error margin of weight prediction and increased spread of pigs' weights within the pen (Fig. 3). As the weight difference in the study pen increased (as a natural consequence of aging of pigs), the error margin associated with weight prediction also increased. This relationship was equally strong ($R^2 = 0.84$) when considering the percentage of error (%) or the relationship between the range (of pig weights in the pen) and absolute predictive error (in kgs) of the WD system was quite strong ($R^2 = 0.89$).

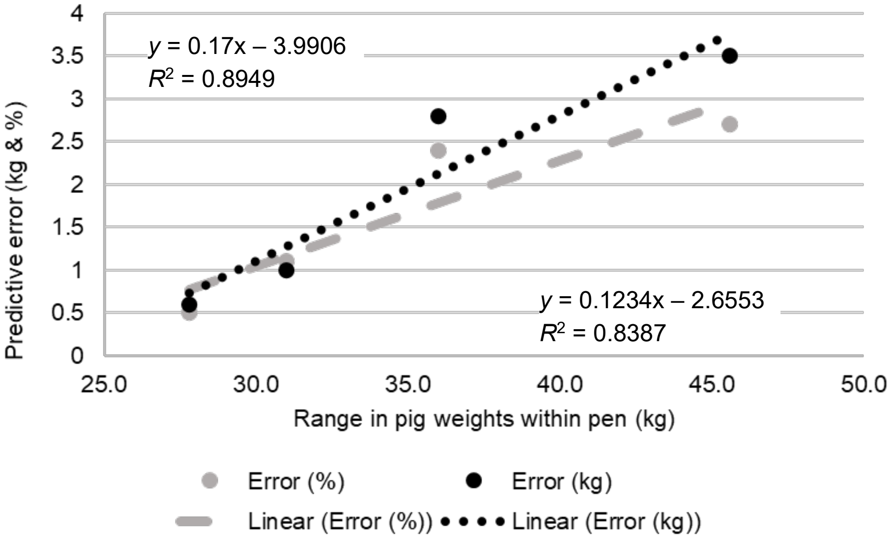

Figure 3. Correlation between increased spread of pig weights (kg) in the pen and increased error margin (as expressed in kg and as percentage).

Various factors, including animal behaviour, camera positioning, and farm management practices, can heavily influence the accuracy of weight monitoring systems. Animal behaviour is particularly important since accurate predictions depend on the even sampling of animals within the pen. When the system captures more images of smaller or larger pigs disproportionately, it can distort the predicted APWs (Lind et al., 2005; Tscharke & Banhazi, 2013a; Tscharke & Banhazi, 2013b). Thus, proper camera placement is crucial to ensure that the visual sampling of pigs is representative and even. Earlier studies often assumed that even sampling would naturally occur within pig pens (Schofield, 1990). However, it has since become clear that that this is not necessarily the case and strategic camera placement is vital for precise weight estimations (Banhazi et al., 2022b).

More importantly, this case study demonstrated that the WD unit was able to detect weight reduction in pigs six days before the clinical signs of a respiratory disease infection were noticed (Fig. 4). According to the WD measurements the study pigs achieved an ADG of 882 g d^{-1} between the 20/03/24 and 16/04/2024 (Table 2). However, between the 17/4/2024 and 30/04/2024 their ADG plummeted to just 286 g d^{-1}. This translated into a 596 g d^{-1} ADG decrease compared to the previous period. The animals were diagnosed with respiratory disease on the 22/04/24, six days after the dramatic reduction in ADG was recorded by the WD system (Fig. 4).

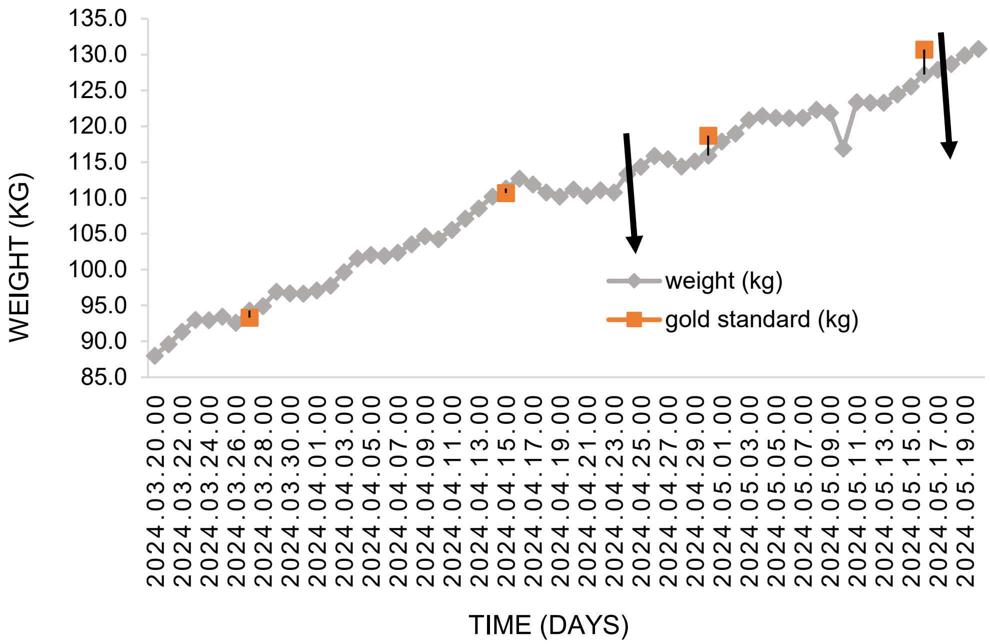

Figure 4. The growth curve observed by the WD system in the study pen. (The arrows indicate the beginning and end of the weight reduction period associated with the respiratory infection. The red dots indicate the manual (gold standard) measurements.).

The typical clinical signs of respiratory infections include reduced feed intake, reluctance to move, coughing, laboured breeding and general respiratory distress. This period of ADG stagnation (when pigs gained only 4.0 kg during that time and actually lost weight between days) led to an approximate 14-day delay in reaching the target slaughter weight, (approx. 130 kg) potentially creating significant financial losses for the producer (Fig. 5). After the 1/05/24 pigs recovered and increased their ADG to 645 g d^{-1} (359 g d^{-1} ADG increase compared to the previous period) until their final weighing day on the 20/5/24. The pigs were subsequently slaughtered on the 21/5/24 achieving an overall ADG of 690 g d^{-1} throughout their growth period (Table 2).

Table 2. ADG measurements obtained throughout the study

Measurement period (dates)	Weight gained (kg)	ADG (g d^{-1})	ADG change (g d^{-1})	Comments
20/03/24–16/04/24	24.7	882		Very good initial ADG
17/04/24–30/04/24	4.0	286	596 decrease	ADG stagnation due to respiratory infection
1/05/24–20/5/24	12.9	645	359 increase	ADG increase due to treatment/recovery
20/03/24–20/5/24	42.8	690		Overall performance of the batch

The primary advantage of weight monitoring systems is their ability to map the growth curve, enabling producers to pinpoint periods of inefficiency and tackle recurring health, nutritional and management problems (Fig. 4). When producers leverage this data to address issues around suboptimal ADGs, the return on investment can be substantial. In this study, the specific economic benefit of the weight estimation was highlighted by the WD instrument's ability to provide an early warning about an impending respiratory disease (Fig. 4).

Previous on-farm experiences demonstrated that regular automated weight monitoring can alert livestock managers about various additional management problems, including housing and general management related issues. (Banhazi et al., 2022a). For example, had the disease been avoided on the Spanish study farm and the pigs maintained their ADG of 882 g d^{-1}, they would have reached the target slaughter weight of 130 kg approximately 14 days sooner (Fig. 5). This could have resulted in considerable cost savings for the producer.

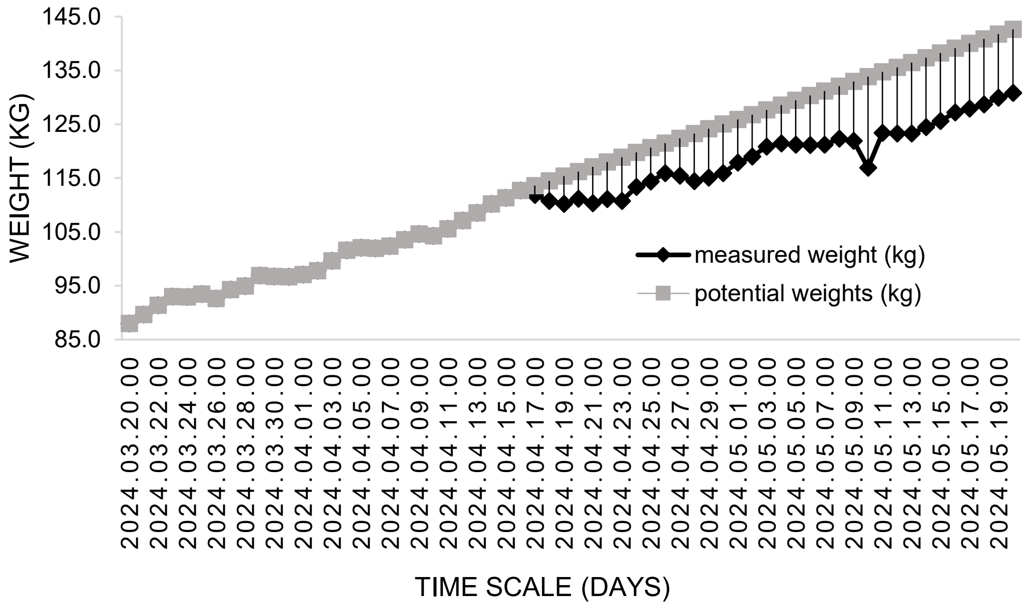

Figure 5. Observed vs. potential growth curves of the pigs in the study pen. The blue line indicates the actual growth curve, while the orange line indicates the potential growth curve, assuming that the initial ADG performance is maintained throughout the growth period.

Farm management practices are crucial in determining the accuracy of weight monitoring systems. For optimal precision, the monitoring team needs to be regularly informed about any changes in farm management, including activities in or around the monitored pen. Such disturbances within livestock buildings can alter animal behaviour, disrupting sampling rates and/or distribution and consequently impacting on weight estimations (Korthals, 2001; Doeschl-Wilson et al., 2005). For instance, during this monitoring period, maintenance work conducted adjacent to the study pen on 10/05/24, caused a brief but noticeable dip in recorded weights. Therefore, any sudden fluctuations in weight should be interpreted in light of these management changes or environmental alterations affecting the animals.

While the reliability of internet connections is usually a problem on many farms, on this particular farm, the internet connection was stable and reliable resulting in a steady data flow.

CONCLUSIONS

These findings highlight the WD system's potential to alert livestock managers to health issues before clinical symptoms manifest. This early detection allows for the timely implementation of mitigation strategies, reducing the adverse effects of diseases on animal welfare and production efficiency. Although the WD instrument has proven dependable in collecting farm data, it's crucial to account for other influencing factors such as camera placement, farm management practices, and animal behaviour. Nonetheless, this case study illustrates that integrating smart technologies into commercial farming can significantly elevate farm management practices and enhance overall profitability.

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Assessment of consumer awareness regarding the implementation of innovative food packaging

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Abstract. Food packaging fulfills many practical functions. They protect against harmful external factors and facilitate transport, distribution on the market, and storage of products in households. They also provide information on food products' type and composition, preparation method, and shelf life. The important role played by packaging contributes to their continuous improvement. An example of this improvement is the implementation of innovative solutions, including active and intelligent packaging. The question remains whether consumers know about these innovative facilities and whether they use them. In search of an answer to this question, a survey was conducted on 210 respondents in the Mazovian region (Poland). The survey aimed to assess consumer knowledge and awareness of active and intelligent food packaging. The study was conducted using the CAWI (Computer-Assisted Web Interview) method. As many as 79% of respondents did not know the term active packaging. It was similar in the case of intelligent packaging - 79% of respondents did not know this type of packaging. Respondents also showed a low level of knowledge regarding the different types of inserts in active packaging and examples of benefits offered by intelligent packaging. The survey results suggest the need to disseminate knowledge and benefits related to active and intelligent packaging.

Key words: active packaging, consumer awareness, intelligent packaging, respondents, survey.

INTRODUCTION

Packaging is one of the key elements of the consumer supply system for food products. This is due to the functions that packaging fulfills. Packaging protects products against harmful external factors. It is an integral part of the food processing chain and helps producers distribute products more efficiently, i.e., transport, storage, and sale, and consumers purchase and use food. Packaging ensures that the product is delivered to the consumer in known quantities and in the expected condition for a specified shelf life. It is a way to make food more attractive, promote its use, and increase sales. Packaging can inform consumers about the type of food being purchased, its preparation, its shelf life, and compliance with relevant food regulations (Robertson, 2012).

In a shop or other point of sale, good packaging, its appearance, and general presentation help attract customers, while functional features can ensure the convenience of using food products. Therefore, food packaging is subject to systematic improvement, becoming an essential link in the sustainable development of the consumer market. Improvements and changes in packaging can bring real benefits to many consumers. These benefits can result from improving the quality of the product sold on the market or increasing the value of the product by improving its appearance and attractiveness to consumers (Stewart, 2007). The attractiveness of a properly designed package can stimulate consumer behaviour when evaluating a product and making purchasing decisions (Becker et al., 2011). Packaging, especially its material, can arouse the consumer's emotional state, which is an important signal identifying acceptance or avoidance of the offered food product (Clark et al., 2021). Many packaging features can influence consumer evaluations of food products. The question is whether these features also include those that identify packaging innovation.

Improvement and innovation are somehow inherent in the development of food packaging. This thesis is confirmed by examples of practical solutions that are gradually appearing in the food packaging space. Such examples are active and intelligent packaging (Barska & Wyrwa, 2016).

The idea of active packaging considers the interaction between the packaging, the product, and the environment. These are systems where the conditions inside the packaging are actively changed to extend the product's durability and maintain the highest possible food quality (Pereira de Abreu et al., 2012).

The idea of intelligent packaging comes down to equipping it with an external or internal indicator that provides information about the history of the packaging, product quality, safety, and location during transport. This type of packaging has an extended information function. Customers have access to up-to-date information about the quality and safety of their food without having to open the packaging (Vanderroost et al., 2014).

Consumers have no problems identifying food packaging (and its features) made of plastic, metal, glass, paper, and cardboard. These types of packaging have been known and widespread for many years. However, are consumers able to identify anything more in food packaging? Are they only interested in fulfilling basic functions through food packaging? Questions formulated in this way may inspire research involving a group of consumers. This research may answer the research problem concerning consumer awareness in improving food product packaging.

The aim of the research study was to assess consumer knowledge and awareness of the active and intelligent packaging of food products available on the market.

The research study tested the following hypothesis: Consumers may have limited awareness of the use of improved food packaging.

Implementing the research study objective and confirming or denying the research hypothesis required designing an appropriate, methodical approach. This approach included preparing a survey questionnaire, selecting a research tool with respondents' participation, conducting a survey on a group of respondents, analyzing and discussing the research results, and formulating conclusions and suggestions.

MATERIALS AND METHODS

Social (human) and marketing research related to knowledge management and consumer decision-making include quantitative and qualitative methods of research studies. In this group of studies, research using a survey questionnaire makes a particularly valuable contribution. This type of research is most suitable for obtaining information about consumers, their preferences, and behaviours on the market, including the food market.

The first stage in the designed research study procedure was formulating questions and proposing a response scheme. These were schemes individually adapted to the specifics of each question. The next stage in the procedure was to conduct a preliminary (pilot) study, consisting of sending surveys to 15 consumers. This stage aimed to check whether respondents had problems understanding the questions and providing answers using the proposed scheme. After analyzing the pilot study results, some survey questions were clarified, and the response format was more precisely adjusted. Then, a large-scale survey was conducted. The large-scale survey was conducted using the Internet. The survey was conducted using the CAWI (Computer-Assisted Web Interview) method, allowing the respondents to provide answers using an online panel. Detailed survey results were initially processed using the Google Forms tool and compiled in an Excel spreadsheet. In the final stage, the spreadsheet data was processed using percentage conversions of responses and figures.

Information about the availability of the survey to be completed was posted on online social media platforms, which made it easier to reach groups of potential respondents interested in participating in the study.

The survey was completely anonymous. Respondents completed the survey individually, independently of other people. They did not know the answers given by other people.

The respondents' opinions on active and intelligent packaging were collected based on six questions. A response scheme was prepared following the way the questions were formulated in the survey. A yes/no response scheme was included for some questions, while for other questions, respondents had several answer options, with the possibility of single or multiple choice.

210 respondents took part in the survey, mainly from the Masovian region (Poland). At the first stage of completing the survey, the respondent was given the option of indicating their age, from the following ranges: 16–18 years, 19–30 years, 31–50 years, and over 50 years. It was assumed that people aged 16–18 may also be active market participants who make purchases and are able to identify different packaging categories. The percentage of participants representing the four age groups was as follows: 16–18 years - 18%, 19–30 years - 65%, 31–50 years - 14%, and over 50 years - 3% of people.

The survey involved 123 women (58.6% of respondents) and 87 men (41.4% of respondents).

At the beginning of the survey, respondents were also asked to provide their education and place of residence (from options for rural areas and cities with different populations). The largest group of respondents had secondary education (49%). The next group was people with higher education (30% of respondents), followed by those with primary education (13%). The fewest consumers had vocational education - 8% of respondents.

Considering the place of residence of the survey participants, the largest group were residents of cities with a population of over 100,000 (38% of respondents). The second largest group was people living in the countryside (village), who comprised 35% of respondents. The group of inhabitants of cities with a population of up to 100,000 was the smallest, accounting for 27% of the respondents.

RESULTS AND DISCUSSION

Results of the survey in the area of active packaging

The question was formulated: Are you familiar with 'active packaging'?

The vast majority, 79% of respondents, were unfamiliar with the term active packaging. Only 21% of respondents knew what active packaging was.

To examine the problem of respondents' knowledge of active packaging in more detail, the survey results were linked to the education of the people filling out the survey. Table 1 presents the results of this comparison.

Table 1. Distribution of responses to the question about knowledge of active packaging for groups of respondents with different education

Respondent's education	Answer option		Relation
	Yes	No	Yes / No
Primary education	1.9%	10.9%	0.17
Vocational education	2.4%	6.2%	0.39
Secondary education	10.0%	39.0%	0.26
Higher education	6.7%	22.9%	0.29
TOTAL	21.0%	79.0%	

Directly comparing the number of responses (percentage of responses) for individual groups with a given education is difficult due to the different numbers of people in each education category. Therefore, the structure of responses was compared based on the percentage of Yes to No responses. The highest ratio of positive responses (Yes) to negative responses (No) was found in the case of the group of respondents with vocational education. On the other hand, this group of respondents was the smallest (8% of the total population of participants), so it isn't easy to draw clear conclusions. It seems more important to draw attention to respondents' generally low knowledge and awareness regarding the active packaging of food products on the market.

Most answers to the question about knowledge of active packaging were 'No'. We can look for justification for this attitude of the survey participants. This result may be caused by the fact that active packaging is not promoted often and sufficiently, and consumer awareness of its existence is low.

Developing a more detailed approach to assessing knowledge about active packaging, the next point in the survey asked: Which of the known types of active packaging are you familiar with? In this question, respondents could choose an answer from eight suggested options. These were seven factors used in active packaging and the eighth option - none of the factors known to the respondent. This question allowed for a maximum of two answers, but could also be one.

The distribution of responses regarding knowledge of active packaging with different types of inserts is presented in Fig. 1. Because respondents could select one or more answers, the sum of percentages does not add up to 100% (Fig. 1).

The distribution of responses in Fig. 1 indicates a relatively low percentage of respondents who confirmed their knowledge of active packaging with the types of inserts distinguished. For the seven types of active packaging included in the survey, on average, only 13% of respondents were familiar with these packages. Almost five times more, or 64% of respondents, stated that they were unfamiliar with any active packaging with the insert listed in the survey.

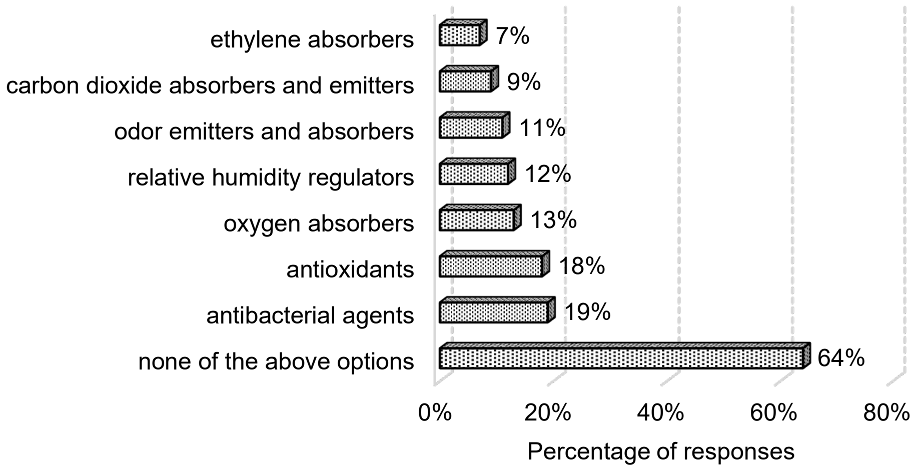

Figure 1. Percentage distribution of responses regarding knowledge of active packaging with different types of inserts.

The high percentage of people unfamiliar with any of the active packaging listed in the survey with the specified insert confirms the results of the answers to the previous question. It concerns the general question: Are you familiar with 'active packaging'? 79% of respondents indicated they were unfamiliar with active packaging.

Results of the survey in the area of intelligent packaging

Respondents were asked whether they were familiar with intelligent packaging in the following survey question. It turned out that the distribution of answers to this question was the same as in the case of active packaging. As many as 79% of respondents did not know what intelligent packaging was, while only 21% of people knew about this packaging.

In more detail, the survey results were analyzed to link respondents' knowledge of intelligent packaging with their place of residence. The results of this comparison are presented in Table 2.

Table 2. Distribution of responses to the question about knowledge of intelligent packaging for groups of respondents with different places of residence

Respondents' place of residence	Answer option Yes	No	Relation Yes / No
Village	8.0%	26.8%	0.30
City up to 100 thousand inhabitants	6.0%	20.7%	0.29
City with more than 100 thousand inhabitants	7.0%	31.5%	0.22
TOTAL	21.0%	79.0%	

Regardless of the respondent's place of residence, in none of the cases did the knowledge of intelligent packaging stand out. For each group of residents, most responses indicate a low understanding of the type of packaging in question. The lowest ratio of responses confirming (yes) to denying (No) knowledge of intelligent packaging was found in the group of respondents from large cities (with a population exceeding 100,000 inhabitants).

The survey also developed more detailed issues related to intelligent packaging. In the next question, respondents were asked to indicate which examples of intelligent packaging they were familiar with. The survey question listed five types of intelligent packaging (to choose from). The sixth option was: 'I do not know any intelligent packaging listed'. Survey participants could choose no more than two of the options provided. For this reason, the sum of the percentages of the individual responses is different than 100%. The percentages of responses regarding examples of intelligent packaging and knowledge about them among respondents are presented in Fig. 2.

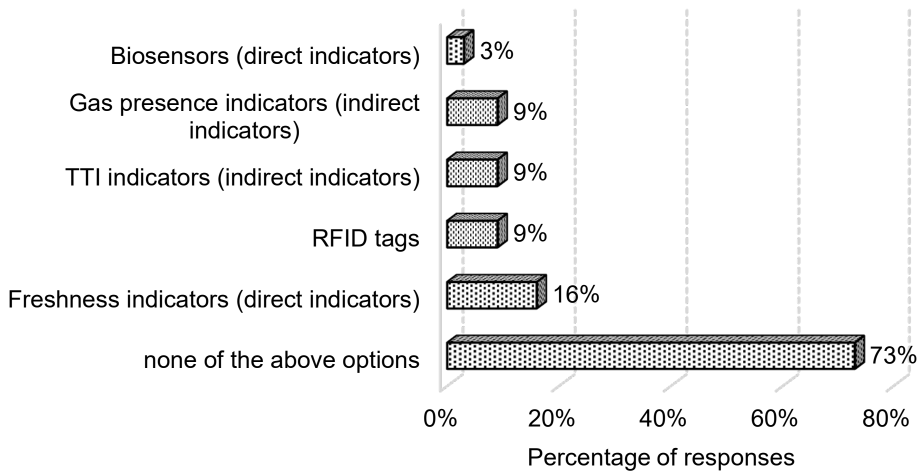

Figure 2. Percentage distribution of responses regarding knowledge of intelligent packaging.

The survey results presented in Fig. 2 indicate respondents have a low level of knowledge regarding sample solutions of intelligent packaging. Knowledge of specific types of intelligent packaging was confirmed by an average of 9% of respondents. Among the five examples of intelligent packaging mentioned, the most well-known was packaging with freshness indicators (confirmed by 16% of respondents), while biosensors were the least well-known (indicated by 3%). However, it is worth noting that compared to the average percentage (9%) of respondents who were familiar with examples of intelligent packaging, the percentage of responses indicating no knowledge of this packaging (73%) was more than eight times higher.

To sum up, the results of this part of the study confirm the research hypothesis that consumers may have limited awareness of the use of improved food packaging.

Other results from the survey on active and intelligent packaging

The next question was to see whether consumers would be more likely to purchase a product when packaged in active or intelligent packaging. This question had three options: yes, no, and I have no opinion.

As many as 79% of respondents chose the option ‘I have no opinion’. This is probably due to limited knowledge of such packaging and its possibilities on the market. Only 17% of respondents indicated that in the case of products packed in such packaging, they are more willing to buy them. Only 4% of respondents considered that access to active and intelligent packaging does not affect their purchases. The results of this part of the survey showed that in the most numerous respondents (19–30 years old), the percentage of people willing to buy products in active or intelligent packaging was 17%. The older age groups had the most people declaring they would buy products in active or intelligent packaging.

The last question in the survey asked about the benefits consumers think are associated with packaging a product in active or intelligent packaging. In this question, respondents had access to six answer options. At least two issues could be selected. The percentage of indications for each option regarding the benefits of packaging food products in active and intelligent packaging is presented in Fig. 3.

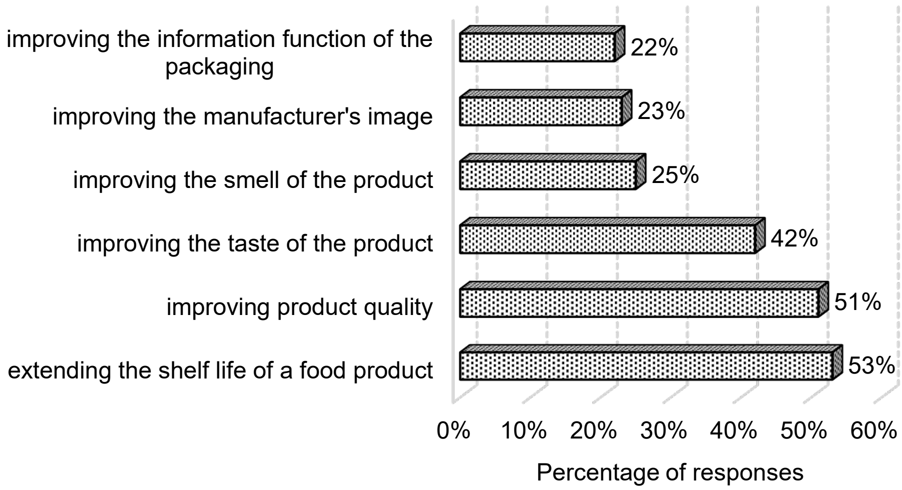

Figure 3. Percentage distribution of responses regarding the benefits of product packaging in active or intelligent packaging.

Despite the limited level of consumer awareness of active and intelligent packaging assumed in the research hypothesis, the question aimed to check what the respondents may associate with these types of packaging. Respondents highlighted (Fig. 3) the importance of factors determining product quality in active or intelligent packaging. Most respondents answered that the key benefits associated with active and intelligent packaging are extending the shelf life of the food product (53% of respondents) and improving the product quality (51% of respondents). In the question under consideration, 42% of respondents highlighted the importance of improving the product's taste using active and intelligent packaging. This result is worth comparing with the next factor (in terms of percentage indication) that respondents emphasized. This factor is the product's smell, which was indicated by 25% of respondents. Does such a comparison indicate that the product's taste is more important to consumers than its smell? It is worth answering these and other questions when discussing the survey results and in the broader context of food product packaging and its assessment.

The evaluation of food packaging can be carried out in different ways, depending on the purpose of the evaluation. Of course, assessing packaging properties in terms of their safety of use in contact with food products (Karmaus et al., 2018) and functionality (Grönman et al., 2013) plays a key role. However, consumer opinions on packaging are also important because they are the recipients of food products. The discussion could address the question: what is the basis for consumers forming opinions about packaging? Is it only the material from which the packaging is made, its attractiveness in terms of appearance, and the information part on the packaging? Many features of food packaging, including its design, size, shape, colours, fonts, etc., can influence the market attractiveness of the product and the consumer decision-making process (Malešević & Stančić, 2021). Consumers' decision-making style interacts with product attractiveness (Soler-Anguiano et al., 2023). When deciding to purchase a food product, the consumer may be guided by the attractiveness of the product packaging (Borishade et al., 2015). Are the characteristics of active and intelligent packaging also responsible for this attractiveness? Our survey results indicated a relatively low level of awareness of respondents regarding active and intelligent packaging. This would suggest that knowledge about active and intelligent packaging rather than the attractiveness of its features could have determined the results of the answers given by the respondents. In the case of active and intelligent packaging, 64% and 73% of respondents, respectively, indicated that they were not familiar with the sample packaging options under consideration.

Is respondents' relatively low knowledge about active and intelligent packaging a surprise? The presented results of our own research reflect the opinions of respondents from the Mazowieckie region in Poland. Research also conducted in Poland, but in the Lubuskie region, showed that the term 'intelligent packaging' was known by 17% of respondents (Barska & Wyrwa, 2016). In the same study, the term 'active packaging' was known by only 4% of respondents. Consumers can come across various packaging representing active and intelligent solutions every day. But how often are consumers unaware they are in contact with practical examples of active and intelligent packaging?

Research on active and intelligent packaging, its improvement, implementation of new projects, and the recognition of this packaging by consumers was undertaken many years ago (Vanderroost et al., 2014). The question remains: To what extent does the development of active and intelligent packaging change consumers' awareness of and knowledge of this packaging? Changes in this consumer awareness are worth systematic research. If the newly created generations of active and intelligent packaging are to be the future of food packaging (Aday & Yener, 2015; Ghaani et al., 2016), then consumers should follow this trend. However, it is important, as indicated by the research of Loucanova et al. (2017), that among consumers, it is possible to identify target groups that are particularly interested in the types of packaging under consideration. As the age of the target group increases, customers are more oriented towards active packaging functions. On the other hand, consumers of decreasing age may be more inclined towards intelligent packaging functions (Loucanova et al., 2017).

Using research methodology involves recognizing various aspects of consumer knowledge and identifying the features of food products, their packaging, and other evaluation elements. The presented research study used a survey method, standard in collecting respondents' opinions. However, the details regarding how questions are formulated, the options for providing answers, and the development of the survey results are crucial. The proposed method of evaluating respondents' answers uses the Kano model, which divides the analyzed packaging functions into mandatory, attractive, neutral, and reverse categories (Loucanova et al., 2017). In evaluating selected food packaging features, a point scale (for example, from 1 to 5) is also considered, which allows us to examine the distribution of point values. The point scale was used to propose a feature significance index - FSI (Gaworski et al., 2021), allowing for a comparison of the examined packaging features in the respondents' assessment. An extension of this approach using respondents' responses on a scale from 1 to 5 is the barrier significance index - BSI (Lamm et al., 2023), which also takes into account the ratio of the percentage of agree and strongly agree ratings (4 and 5) to the percentage of strongly disagree and disagree ratings (1 and 2).

In our survey, a wide age range of respondents was considered. This requires an appropriate approach to interpreting the research study's results considering age groups. Analyzing the survey results through the criterion of age groups makes a valuable contribution to assessing the diversity of preferences and behaviour of respondents (consumers) of different ages in the considered research area (Baruk & Iwanicka, 2016). In opinion surveys, it seems equally essential - due to the comparison of results - to consider other criteria characterizing respondents. Such a criterion may be not only education but, in the case of higher education, also the type of studies completed (Gaworski & Turbakiewicz, 2020). In survey research, it may be crucial to identify the main stakeholder groups clearly. This reasonable approach to many survey studies allows for the collection of reliable research material, its discussion, and the formulation of valuable observations (Johnson et al., 2025).

The respondents in this study came from different places of residence, which did not translate into differentiation of the results regarding knowledge about active and intelligent packaging. However, this does not mean that place of residence cannot be an essential criterion for comparison in survey studies. Suppose the aim of the study is, for example, to compare the knowledge of respondents and their access to certain food products. In that case, the region of residence of the respondents may be a key criterion for comparison (Kamińska et al., 2016). Another example is comparing the impact of food packaging on the buying behaviour of rural and urban consumers (Sehrawet & Kundu, 2007); rural consumers were more critical of packaging, believing that it could mislead buyers and cause environmental hazards.

The consumer awareness problem of active and intelligent packaging addressed in the survey is an example of research on contemporary problems in the consumer market. These contemporary problems in the case of packaging have a much broader dimension and raise the issue of consumer response to environmentally friendly food packaging (Ketelsen et al., 2020), biodegradable packaging (Bojanowska & Sulimierska, 2023), packaging recycling (Ruokamo et al., 2022), the connection between packaging and food waste (Williams et al., 2020) and others.

Consumer knowledge about the current problems of food packaging development should be part of the transformation of the food chain (Gaworski, 2006), where the implementation of sustainable packaging should play a key role (Boz et al., 2020).

Food product packaging should focus the attention of all market participants, consumers, and food producers. Therefore, it is essential to develop research that considers brand owners and their approach to implementing modern and improved food packaging. In this case, the issue of brand owners' awareness of introducing food products in active and intelligent packaging to the market and their acceptance and popularization can be raised (Klimchuk & Krasovec, 2013). Attractive graphic designs of packaging proposed by brand owners can play a special role in disseminating and promoting knowledge about active and intelligent packaging (Wells et al., 2007; Wu, 2015). The flow of information - via food packaging - between brand owners and consumers could be an area for further research studies. These studies can make a valuable contribution to the sustainable development of the food market.

CONCLUSIONS

Many active and intelligent packaging features are not sufficiently recognized by consumers, as confirmed by research on a group of respondents in the Masovian region of Poland.

The survey results suggest the need to disseminate knowledge about active and intelligent packaging specifics. The source of dissemination of knowledge about the groups of packaging under consideration may be programs and other forms of knowledge transfer in the mass media.

The presentation of the benefits of using active and intelligent packaging may inspire increasing interest in this type of packaging among consumers.

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Deciphering the paradox: the role of organizational identification in workaholism versus burnout

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Abstract. This study explores the complex relationship between organizational identification, workaholism, and burnout. Organizational identification, denoting individuals' psychological connection to their workplace, significantly influences their work-related attitudes and behaviors. While it often correlates with workaholic tendencies characterized by excessive work engagement, it does not directly cause burnout - a state of emotional exhaustion due to chronic work-related stress. Utilizing a qualitative grounded theory approach, we conducted a comprehensive literature review using Scopus, analyzing 141 articles to identify the antecedents of workaholism, burnout, and organizational identification. Our findings reveal that organization-related factors, such as job demands, social support, job autonomy, and organizational culture, significantly impact both organizational identification and burnout. Conversely, workaholism is primarily driven by personal factors like perfectionism, low self-esteem, and family background. These insights suggest that fostering positive organizational factors can enhance organizational identification and mitigate burnout, while addressing personal factors is crucial in managing workaholism. This research contributes to the economic understanding by highlighting the role of organizational culture and job design in employee well-being, which can impact productivity and organizational performance. The study underscores the importance of developing interventions that balance organizational identification with healthy work habits to promote a resilient and productive workforce. Future research should focus on empirical tests to better understand the influence of organizational and personal factors on these constructs, paving the way for more effective strategies to foster employee well-being.

Key words: burnout, organizational identification, workaholism, stress.

INTRODUCTION

Organizational identification, denoting the depth of individuals' sense of belonging and connection to their workplace, profoundly influences work-related attitudes and behaviors (Ashforth & Mael, 2024). Despite its positive impacts, organizational identification often correlates with workaholic tendencies and varying burnout levels, presenting a paradox that this study aims to unravel. Strong organizational identification often correlates with workaholic tendencies, wherein individuals may feel compelled to overwork to fulfill job demands and contribute to organizational success (Mazzetti et al., 2023). This association between organizational identification and workaholism has been substantiated by Avanzi et al. (2012), who uncovered a curvilinear relationship suggesting that both low and high levels of identification may lead to heightened workaholic behavior compared to moderate levels.

Workaholism is positively associated with burnout as individuals driven by excessive work demands may experience higher levels of stress and exhaustion (Schaufeli et al., 2009; Schaufeli & Taris, 2014; Clark et al., 2016). However, while organizational identification may indirectly mitigate burnout by fostering job satisfaction and social support (Lee & Ashforth, 1996; Halbesleben & Buckley, 2004; Van den Broeck et al., 2008), it does not directly cause burnout (Caprar et al., 2022).

While strong organizational identification can encourage workaholic tendencies, it may also offer social-psychological resources, such as a sense of support and purpose, that can mitigate the potential for burnout (Geidelina-Lugovska & Cekuls, 2023). Understanding and addressing the factors that influence the interplay between workaholism and burnout, particularly under conditions of heightened organizational identification, is critical to fostering healthier workplace environments.

In essence, organizational identification plays a dual role in shaping employee behavior and well-being. It may predispose individuals to excessive work behaviors while simultaneously providing buffers against the negative effects of such tendencies, making the relationship between organizational identification and burnout inherently complex.

Despite substantial research on organizational identification, workaholism, and burnout, the mechanisms underlying their interrelations remain poorly understood. Recent studies (Caprar et al., 2022; Mazzetti et al., 2023) have emphasized the importance of understanding the interplay between these constructs and identifying strategies to alleviate the adverse effects of workaholism on burnout, which are critical for promoting a healthy and productive work environment.

This study seeks to address the gap identified by Caprar et al. (2022) regarding the paradoxical nature of organizational identification's outcomes. Specifically, it examines why high organizational identification fosters workaholism but does not consistently lead to burnout. By employing a comprehensive content analysis of peer-reviewed literature, this research aims to identify antecedents of workaholism, burnout, and organizational identification, offering insights into their complex dynamics. The findings will contribute to the development of organizational strategies that balance employee dedication with well-being, mitigating the risks of workaholism and burnout.

MATERIALS AND METHODS

This section outlines the methodological approach employed to systematically analyze the antecedents of workaholism, burnout, and organizational identification using content analysis. The process was designed to ensure comprehensive coverage and reliability in capturing relevant scholarly insights.

Methodological Framework:

- Approach: Qualitative grounded theory.
- Sampling: Theoretical sampling.

- Data Source: Scopus database.
- Coding: Open and axial coding.
- Validation: Intercoder reliability and peer debriefing.

A qualitative research design was employed to identify a gap in the existing scientific literature concerning this relationship. Grounded theory was deemed the most appropriate approach, facilitating the derivation of theory directly from the data through an inductive process. This method offers several advantages, such as the ability to collect rich, detailed data that provides deep insights into complex phenomena (Patton, 2014). Additionally, qualitative methods are inherently flexible and adaptable, allowing researchers to adjust their approach in response to emerging findings (Denzin & Lincoln, 2011).

Grounded theory focuses on developing a theory that emerges systematically from the collected and analyzed data (Glaser & Strauss, 1967; Charmaz, 2006). The research commenced with theoretical sampling, ensuring that data collection and analysis were iterative and informed by the evolving framework. To perform content analysis, a scientific article search was conducted using Elsevier's Scopus database, chosen for its comprehensive collection of resources and recognition as the most extensive repository of peer-reviewed literature (Mongeon & Paul-Hus, 2016; Jagtap, 2019). Considering an 84% overlap in search results between Scopus and Web of Science, Scopus was selected as the preferred option for this investigation (Gavel & Iselid, 2008). Initially, relevant articles were identified using a range of keywords.

The criteria used for the inclusion of studies in the review were:

- The paper is based on empirical data or a literature review.
- The paper discusses the antecedents of workaholism/burnout/organizational identification.
- Published journal or conference papers only (not editorials, book chapters, theoretical papers, etc.).
- Published in the English language.

The search was performed within abstracts, titles, and keywords.

Given that the meanings and interpretations of terms can evolve over time, and considering ongoing debates surrounding the application of content analysis, a pivotal question arises as to whether the analysis should be limited to manifest content - clearly observable and measurable elements – or whether it should also encompass latent content that captures deeper, underlying meanings. In the latter case, the analytical approach delves into an interpretive examination of the tangible data's symbolic significance.

The optimal resolution to the dilemma concerning the choice between manifest and latent content involves advocating for a dual approach, incorporating both whenever feasible. In this context, each content unit undergoes parallel scrutiny through both methods, contingent upon the condition that the coding procedures (discussed subsequently) for both manifest and latent content demonstrate reasonable validity and reliability. Consequently, the decision was made to employ manifest and latent coding, as researchers are compelled to comprehend documents' literal and latent meanings.

To achieve the primary objective of content analysis, three distinct research projects were conducted:

1. **Identifying the antecedents of workaholism**

The first research project was performed to identify the antecedents of workaholism. By employing the keywords ‘workaholism’ AND ‘antecedents’, 72 documents were retrieved from Elsevier's Scopus database. The search period was not constrained; however, upon closer examination, it was determined that as of 2014, the antecedents of workaholism remained unclear, with a limited empirical foundation for the proposed antecedents (Andreassen, 2014). This observation was substantiated by Mazzetti, Schaufeli, and Guglielmi, who noted the ‘ongoing conceptualization of workaholism’ in the same year. Additionally, an analysis of search results in Elsevier's Scopus database, using the specified keywords, revealed that 2014 was a pivotal year for workaholism antecedents research, signaling an upsurge in studies on this topic post-2014.

The refined search yielded 49 results, spanning from 2014 to December 2023. The articles underwent analysis and screening based on predetermined inclusion criteria. Following a meticulous review of titles and abstracts to ascertain each paper's scope and considering those meeting the inclusion criteria, 20 articles were chosen for further in-depth investigations. Additionally, eleven articles were identified through a thorough reference search.

2. **Exploring the antecedents of burnout**

The second research project was performed to identify the antecedents of burnout. By employing the keywords ‘burnout’ AND ‘antecedents’, 573 documents were retrieved from Elsevier's Scopus database in January 2024. The search period was not restricted. Upon analyzing the search results, it became evident that research on antecedents of burnout experienced a notable surge in 2009, contributing to a total of 485 research articles between 2009 and 2024.

However, after a more thorough investigation, it became apparent that many research articles are related to different types of burnouts, extending beyond the organizational context (e.g., parental burnout, athlete burnout, etc.). Consequently, a decision was made to apply a filter and restrict the subject area to Business, Management, and Accounting, as well as Social Sciences, resulting in 220 documents found from 2009-2024. The articles underwent rigorous analysis and screening, adhering to predetermined inclusion criteria. After a meticulous review of titles and abstracts to delineate each paper's scope and subsequent selection based on meeting the inclusion criteria, 54 articles were chosen for subsequent in-depth investigations. Furthermore, an additional sixteen articles were identified through a comprehensive reference search.

3. **Identifying the antecedents of organizational identification**

The third research project was executed to discern the antecedents influencing organizational identification. A systematic query using the conjunction of the keywords ‘organizational identification’ AND ‘antecedents’ was conducted, retrieving 172 documents from Elsevier's Scopus database in January 2024. The temporal scope of the search was not delimited, encompassing findings from 1992 to 2024; given the specialized nature of research concerning organizational identification, a comprehensive approach was adopted, encompassing all accessible resources for an exhaustive inquiry.

All identified resources underwent stringent scrutiny and screening procedures, aligning with pre-established inclusion criteria. A meticulous evaluation of titles and abstracts was undertaken to delineate the thematic scope of each paper. After this preliminary assessment, articles were selected based on their alignment with the inclusion criteria, identifying 38 pertinent articles for subsequent in-depth analysis. Furthermore, two additional articles were discovered by examining references in the selected literature.

After determining the theoretical sampling, the open coding stage commenced. During this phase, the text was segmented into individual excerpts to identify antecedents of organizational identification, workaholism, and burnout. These codes were organized into broader categories in the subsequent axial coding stage. For instance, expressions such as ‘High job demands, such as long working hours, tight deadlines, and heavy workloads, can increase the risk of workaholism and burnout’ (Molino et al., 2016) and ‘High workload is a common antecedent of burnout, especially in jobs that require long hours, tight deadlines, and high pressure to perform’ (Maslach et al., 2001) were initially coded as ‘workload’ and ‘job demands’ during open coding. These were later consolidated into the ‘Workload/Job demands’ category during axial coding. Similarly, phrases like ‘The culture of an organization can have a significant impact on the well-being and identification of its employees’ (Nishii & Mayer, 2009) and ‘A positive organizational culture that values work-life balance and employee well-being can decrease workaholism and burnout and increase organizational identification’ (Schaufeli et al., 2008a) were coded as ‘organizational culture’ in the open coding stage and retained as the same category name in the axial coding stage.

The coding process continued until theoretical saturation was achieved. To enhance the study’s validity and reliability, two key measures were implemented. First, an intercoder reliability process ensured internal validity by verifying consistent interpretation of codes over time or among different researchers. As Richards (2009) explains, intercoder reliability ‘ensures that you are reliably interpreting a code in the same way across time, or that you can rely on your colleagues to use it in the same way’. Second, a peer debriefing process was employed to identify and address potential biases and assumptions within the research.

Following the axial coding stage, 7 categories were identified for the first search, which utilized the keywords ‘workaholism’ AND ‘antecedents’, 11 categories emerged for the second search, using the keywords ‘burnout’ AND ‘antecedents’, and 11 categories for the third search with keywords ‘organizational identification’ AND ‘antecedents’. These identified categories formed the basis for further analysis.

RESULTS AND DISCUSSION

Qualitative content analysis, specifically frequency analysis, was performed to discern antecedents associated with workaholism, burnout, and organizational identification. Fig. 1 illustrates the research-specific approach for conducting content analysis. After identifying valuable resources and screening procedures, 141 sources were selected for thorough analysis.

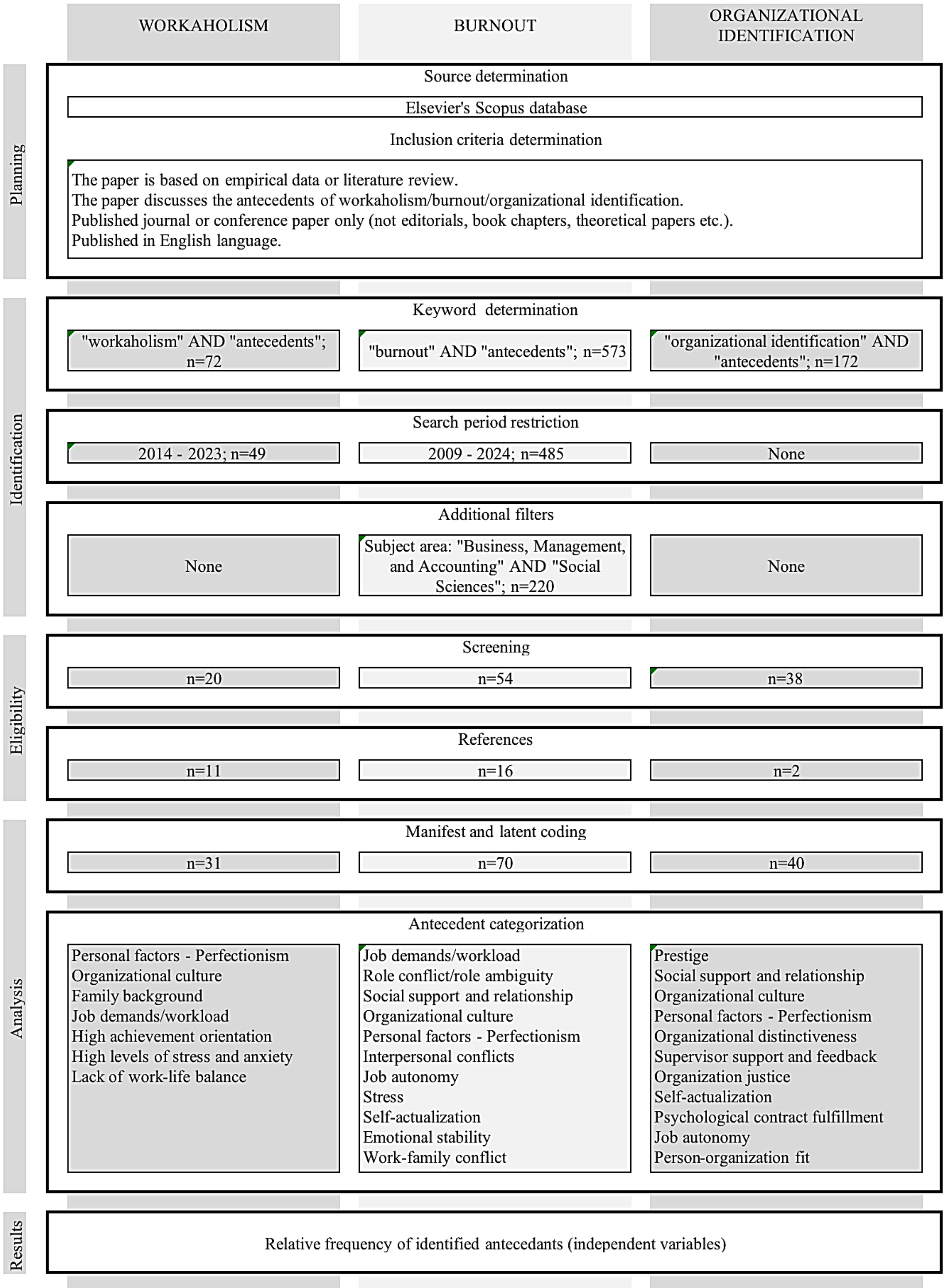

Figure 1. Research-specific approach for conducting content analysis.

Source: Authors' construct, based on performed content analysis, 2024.

Antecedents of workaholism

31 scientific research papers were deemed eligible for a thorough analysis to identify antecedents of workaholism. Fig. 2 shows the relative frequency of the identified antecedents of workaholism.

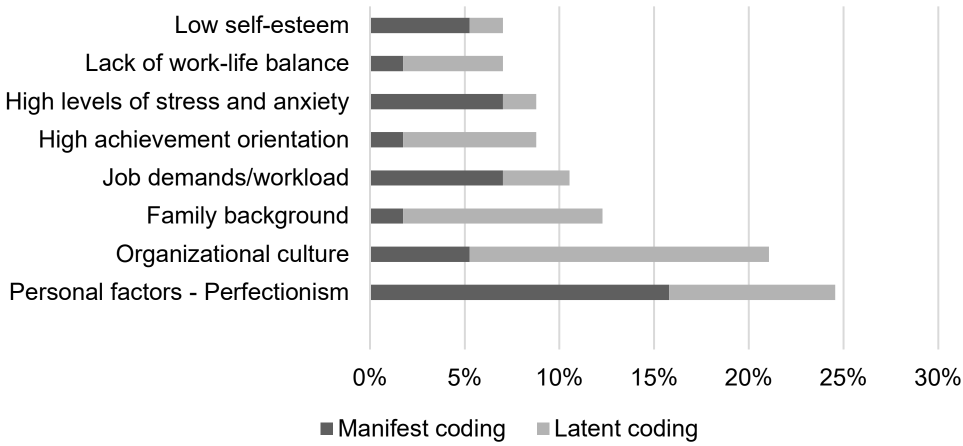

Figure 2. Relative frequency of the identified independent variables - antecedents of workaholism. Source: Author's construct, based on performed content analysis, 2024.

Perfectionism, defined by an unwavering pursuit of flawlessness and an aversion to delegating tasks, emerges as a salient antecedent of workaholism (Shimazu et al., 2015). Individuals exhibiting perfectionist traits are predisposed to engaging in excessive work behaviors driven by the relentless pursuit of perfection (Clark et al., 2016). The convergence of perfectionism with high achievement orientation, characterized by ambitious goal-setting and a fervent commitment to surpassing them, further fuels workaholic tendencies (Mudrack & Naughton, 2001).

Empirical evidence underscores the predictive role of perfectionism in developing workaholism over time (Molinaro et al., 2022). Personality factors associated with achievement motivation contribute significantly to the manifestation of perfectionism-driven workaholism (Mazzetti et al., 2014; Aziz & Moyer, 2018). Notably, the interplay between perfectionism and workload predicts workaholism among managerial personnel (Girardi et al., 2018).

Organizational culture profoundly influences workaholism, with environments emphasizing prolonged working hours and constant availability fostering a culture of overwork (Shimazu et al., 2014). Competitive work environments, where success is equated with long hours and relentless dedication, promote workaholic behaviors among employees (Akutsu et al., 2022).

Structural equation modeling studies reveal a robust association between workload, cognitive demands, emotional demands, and customer-related social stressors with workaholism (Molino et al., 2016). Conversely, organizations prioritizing employee well-being and work-life balance actively discourage workaholic tendencies (Van der Hulst & Geurts, 2001).

Family background shapes workaholic tendencies, particularly in environments where hard work is esteemed and rewarded (Robinson, 1998). Individuals raised in such families internalize the belief that relentless endeavor is imperative for success, thus fostering a predisposition towards workaholism (Xu et al., 2023).

Positive reinforcements during childhood, where hard work is linked to recognition and success, establish a pattern of workaholism that may persist into professional life (Xu et al., 2023). Moreover, the high dependency ratio within familial dynamics contributes to workaholism, as individuals strive to uphold socially endorsed work practices and avoid perceptions of indolence (Adongo et al., 2024).

Workload, encompassing the volume and intensity of tasks, is a significant antecedent to workaholism (Tziner et al., 2019). Higher workloads, particularly when coupled with emotionally or cognitively taxing job requirements, heighten the propensity for workaholic behaviors (Morkevičiūtė et al., 2021). Organizational climates characterized by overwork normalize excessive workloads, perpetuating workaholic tendencies among employees (Akutsu et al., 2022).

The lack of work-life balance exacerbates workaholism, as individuals prioritize professional obligations over personal leisure and relationships (Andreassen, 2014). This imbalance, often perpetuated by societal expectations and organizational cultures, fosters a cycle of excessive work engagement and neglect of personal well-being (Clark et al., 2016).

Antecedents of burnout

70 scientific research papers were deemed eligible for a thorough analysis to identify antecedents of burnout. Fig. 3 shows the relative frequency of the identified antecedents of burnout.

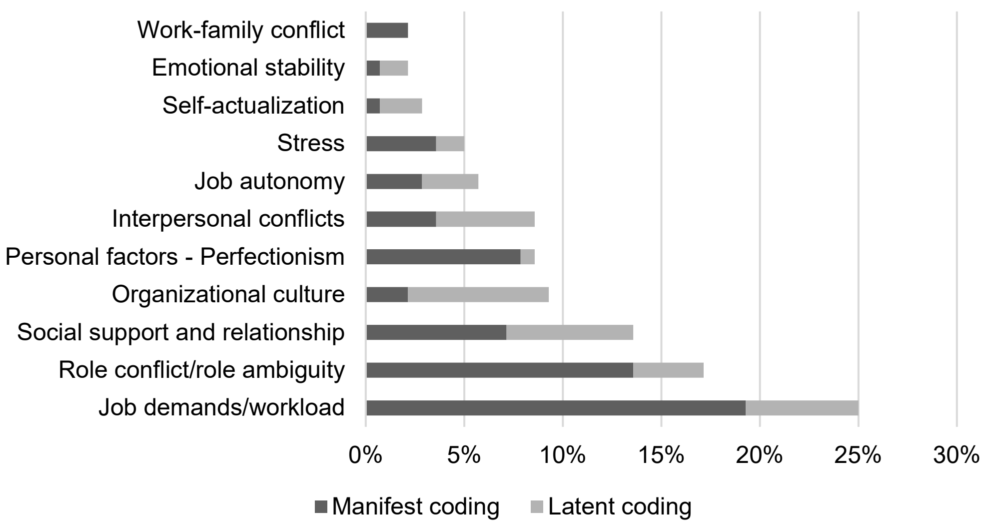

Figure 3. Relative frequency of the identified independent variables - antecedents of burnout.
Source: Author's construct, based on performed content analysis, 2024.

High workload and excessive job demands are primary contributors to burnout. The research underscores the detrimental effects of prolonged exposure to heavy workloads, tight deadlines, and constant pressure, leading to diminished job satisfaction and increased stress levels (Maslach et al., 2001). Adebusuyi (2023) highlighted a direct link between job overload and burnout among police officers, emphasizing the need for effective workload management strategies to mitigate burnout risk.

Unclear roles and conflicting expectations within the workplace contribute to stress and anxiety, exacerbating burnout risk. Role conflict and ambiguity lead to emotional strain and decreased job satisfaction (Lee & Ashforth, 1996; Adebusuyi, 2023). Asfahani's (2023) study on Jordanian teachers further corroborated the detrimental effects of role conflict on burnout levels, emphasizing the importance of role clarity in preventing burnout.

Strong social support networks and positive interpersonal relationships serve as protective factors against burnout. Employees who feel supported by colleagues and supervisors are better equipped to cope with stress and adversity, reducing burnout vulnerability (Szigeti et al., 2023). Conversely, interpersonal conflicts and lack of support exacerbate burnout risk (Ayachit & Chandra, 2023). Fostering a supportive work culture and providing resources for conflict resolution are essential for mitigating burnout risk.

Organizational culture significantly influences burnout outcomes. Cultures prioritizing employee well-being and open communication tend to have lower burnout rates (Bakker & Leiter, 2017). Conversely, toxic work cultures characterized by excessive competition and punitive management practices contribute to burnout and turnover (Bakker et al., 2023). Creating a positive work environment that values employee engagement and recognizes achievements is crucial for preventing burnout.

Individual characteristics, such as perfectionism, play a role in burnout susceptibility. Perfectionistic tendencies increase the risk of burnout by fostering unrealistic expectations and self-imposed pressure (Stoeber & Gaudreau, 2017). Promoting self-awareness and supporting perfectionists can help mitigate the burnout risk associated with this trait.

Conflict within the workplace disrupts workflow and contributes to burnout by creating emotional strain (Szigeti et al., 2023). Addressing interpersonal conflicts through effective communication and conflict resolution training is essential for preventing burnout and promoting positive work relationships.

Job autonomy is a crucial determinant of burnout risk. High levels of autonomy empower employees and foster job satisfaction, while micromanagement increases burnout vulnerability (Bakker & Costa, 2014). Providing opportunities for autonomy and trusting employees to manage their work effectively are key strategies for reducing burnout risk.

Chronic stress depletes emotional and physical resources, leading to burnout (Maslach et al., 2001). Work-related stressors trigger the body's stress response and impair coping mechanisms (Bakker et al., 2023). Implementing stress management programs and promoting work-life balance are essential for mitigating burnout risk.

Self-actualization protects against burnout by promoting engagement and resilience (Deci & Ryan, 2000). Providing opportunities for personal growth and purposeful work can help prevent burnout.

Individual differences in emotional stability influence burnout susceptibility (Bakker et al., 2023). Emotional stability buffers against burnout by promoting adaptive coping strategies (Bakker et al., 2023).

Balancing work and family responsibilities is a significant source of stress (Bakker & Demerouti, 2017). Mitigating work-family conflict through flexible work arrangements and support programs is essential for preventing burnout.

Antecedents of organizational identification

40 scientific research papers were deemed eligible for a thorough analysis to identify antecedents of organizational identification. Fig. 4 shows the relative frequency of the identified antecedents of organizational identification.

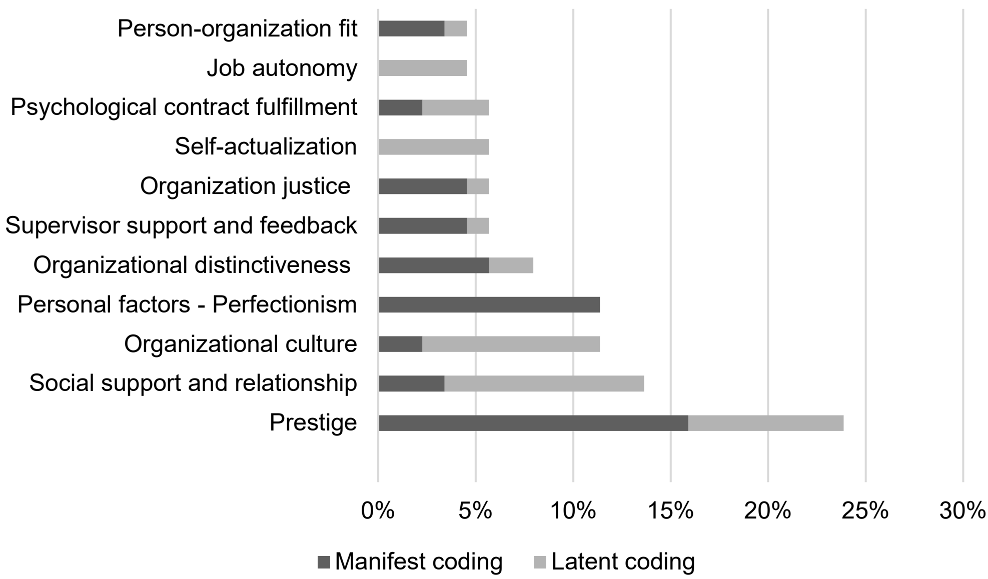

Figure 4. Relative frequency of the identified independent variables - antecedents of organizational identification.

Source: Author's construct, based on performed content analysis, 2024.

Organizational prestige, reflecting perceived status and success, significantly influences organizational identification. Employees gravitate towards organizations perceived as prestigious, fostering a sense of pride and attachment (Mael & Ashforth, 1992). Studies affirm a positive correlation between organizational prestige and stronger organizational identification (Vora et al., 2005).

Organizational distinctiveness, manifested through perceived prestige and distinct characteristics, fosters a sense of loyalty and pride among members, enhancing organizational identification (Tsui & Ngo, 2015). Fairness in organizational processes enhances organizational identification (Bergami & Morandin, 2019). Meaningful work and participation in decision-making contribute to organizational identification (Fuller et al., 2006; Hwang & Jang, 2020). Granting employees autonomy enhances organizational identification (Chawla & Srivastava, 2016).

Positive interactions and perceived support within the workplace foster a sense of belonging and organizational identification (He & Brown, 2013; Bakker & Demerouti, 2017). Employees who feel acknowledged by their supervisors exhibit heightened organizational identification, enabling them to navigate work demands with resilience (Halbesleben et al., 2004). Supportive relationships between supervisors and employees bolster organizational allegiance and commitment (Kazmi & Javaid, 2022). Meeting employees' expectations fosters stronger identification with the organization (Zhu et al., 2017).

Organizational cultures emphasizing employee well-being and work-life balance cultivate stronger organizational identification (Schaufeli et al., 2008b; Nishii & Mayer, 2009). Organizations can bolster employee engagement and performance by fostering a positive culture while mitigating burnout risk.

Individual characteristics, including the need for affiliation and organizational self-esteem, shape organizational identification (Güleryüz & Aydın, 2015). Perceptions of organizational attributes, such as attractiveness and prestige, further influence identification with the organization (He & Brown, 2013). Aligning individual values and organizational environment fosters organizational identification (Güleryüz & Aydın, 2015).

Various factors, including value congruence, psychological ownership, and intrarole conflict, contribute to organizational identification (Jones & Volpe, 2011; Bergami & Bagozzi, 2000).

The interplay between organizational identification, workaholism, and burnout

In the intricate landscape of organizational psychology, the antecedents of workaholism, burnout, and organizational identification collectively shape employee well-being, commitment, and performance. Understanding the interplay of various factors at the individual, interpersonal, and organizational levels is essential for fostering a holistic approach to workplace health and productivity.

Organizational culture plays a pivotal role in shaping all three constructs: workaholism, burnout, and organizational identification. Cultures emphasizing long working hours or neglecting work-life balance are significant predictors of burnout (Halbesleben & Buckley, 2004; Demerouti et al., 2021). Conversely, cultures that prioritize work-life balance are associated with enhanced organizational identification, which can influence both workaholism and burnout (Schaufeli et al., 2008b; Nishii & Mayer, 2009).

Organizational identification, critical for fostering employee allegiance, is shaped by several factors. Social support and relationships with colleagues and supervisors play a key role in cultivating positive organizational connections (George & Chattopadhyay, 2005; He & Brown, 2013). Elements such as supervisor support, feedback, organizational justice, person-organization fit, psychological contract fulfillment, and overall satisfaction with the organization collectively contribute to shaping organizational identification (Olkkonen & Lipponen, 2006; Edwards & Peccei, 2010; He & Brown, 2013; Chawla et al., 2016; Hwang & Jang, 2020). These factors underscore the intricate relationship between individuals and their organizations.

Job-related characteristics - including job involvement, task identity, autonomy, and job demands - highlight the nuanced relationship between work-related factors and organizational identification (Katrinli et al., 2009; Molino et al., 2016). High job demands, such as heavy workloads, tight deadlines, and challenging responsibilities, are well-documented contributors to burnout, which is characterized by emotional and physical exhaustion (Maslach et al., 2001; Shimazu et al., 2010). In contrast, job autonomy serves as a protective factor, reducing burnout risk by enhancing perceived control over work (Maslach et al., 2001; Bakker & Costa, 2014). However, unclear roles, interpersonal conflicts, and inadequate social support exacerbate burnout risks (Eisenberger et al., 1986; Halbesleben & Buckley, 2004; Maslach & Leiter, 2008).

Workaholism often stems from a lack of work-life balance, driven by the relentless pursuit of professional achievement. Conflicts between work and family responsibilities further amplify burnout risks for workaholics (Andreassen et al., 2010; Clark et al., 2016). Family background and workload also contribute to the complex nature of workaholism (Robinson, 1998; Shimazu et al., 2015; Morkevičiūtė et al., 2021). Psychological factors, such as low self-esteem, can drive excessive work as individuals seek validation through professional success (Machlowitz, 1980; Xu et al., 2023). Coping mechanisms, such as using work to manage stress and anxiety, further illustrate the intricate connection between emotional well-being and workaholism (Shimazu et al., 2010). High achievement orientation, marked by ambitious goals and perfectionism, fuels workaholic behaviors (Mudrack, 2004; Adongo et al., 2024). Perfectionism, in particular, is a prominent antecedent, pushing individuals toward excessive work in pursuit of flawlessness (Shimazu et al., 2015; Clark et al., 2016).

Similarly, personal factors such as high anxiety levels, perfectionism, and neglect of personal well-being exacerbate burnout risks (Bianchi et al., 2015; Schonfeld & Bianchi, 2016). Personality traits, including agreeableness, neuroticism, and the need for affiliation, also influence organizational identification, further contributing to the complex interplay between personal and organizational factors (Andreassen et al., 2010; He & Brown, 2013).

Fig. 5 shows the identified antecedents of workaholism, burnout, and organizational identification discovered through the content analysis.

The findings reveal that organizational factors - including job demands, social support, job autonomy, and organizational culture - significantly influence both organizational identification and burnout. For managers and organizational leaders, fostering a supportive work environment that balances job demands with adequate social support and autonomy is crucial. Such practices can mitigate burnout risks while promoting healthy organizational identification. Encouraging these organization-related factors can enhance employee commitment while lowering burnout risks. In contrast, workaholism appears primarily driven by personal factors such as perfectionism, low self-esteem, and family background. Consequently, higher levels of organizational identification are more closely linked to workaholism than burnout.

To address these dynamics, organizations should implement policies that promote work-life balance, such as flexible work hours and employee wellness programs. Training programs aimed at improving supervisors' abilities to provide constructive feedback and support can further strengthen organizational identification while reducing burnout risks. These strategies can create a healthier, more productive workplace that supports employee well-being and fosters sustainable organizational success.

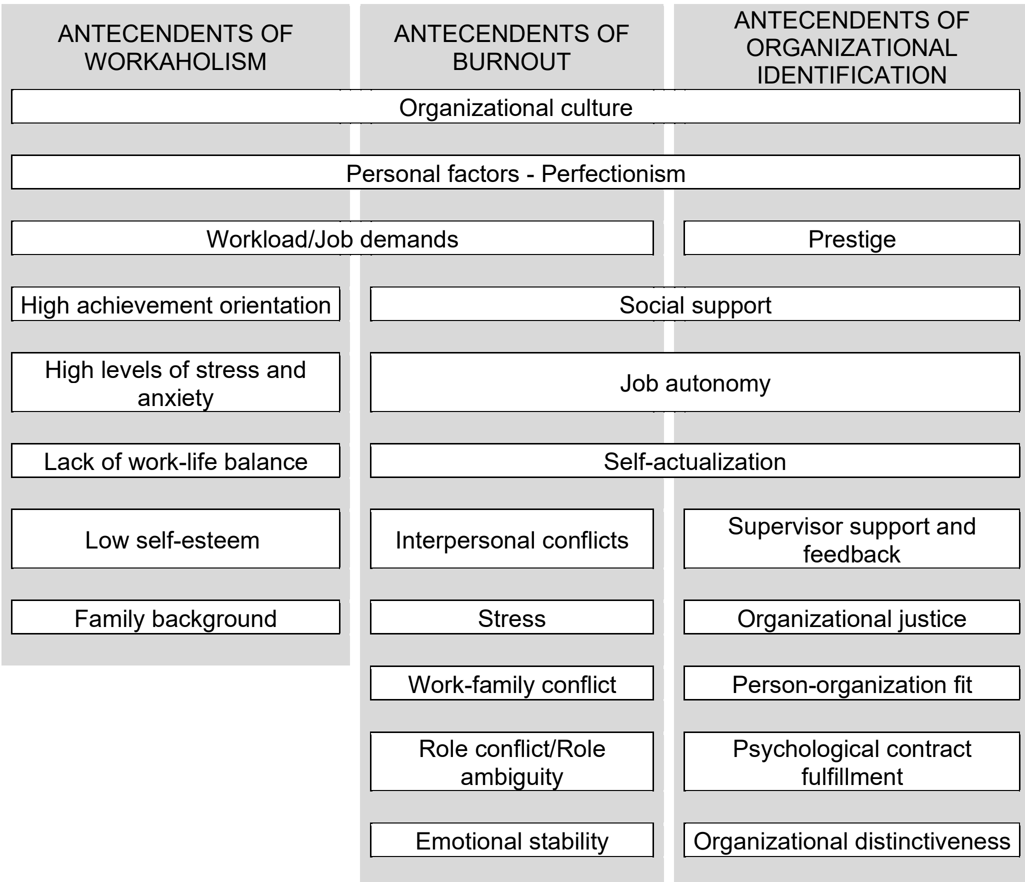

Figure 5. Identified antecedents of workaholism, burnout, and organizational identification.
Source: Author’s construct, based on performed content analysis, 2024.

This article contributes a novel perspective to the existing body of scientific literature, thereby paving the way for further exploration into the intricate relationship between organizational identification, workaholism, and burnout.

In summary, recognizing and strategically addressing these diverse antecedents are paramount for organizational leaders and practitioners to create interventions and strategies that foster a positive organizational identity while addressing challenges posed by specific factors. A holistic approach to employee well-being, work-life balance, and organizational commitment is essential for cultivating a thriving and resilient workplace.

CONCLUSIONS

This analysis underscores the complexity of factors influencing workaholism, burnout, and organizational identification. Recognizing these factors is essential for developing interventions that foster a positive organizational identity while addressing the challenges posed by specific antecedents. Future research should explore empirical tests to better understand the influence of organizational and personal factors on these constructs, paving the way for more effective strategies to foster employee well-being and organizational performance.

This study exclusively relied on the Scopus database, which, while comprehensive, may have led to the omission of relevant literature available in other sources. As a result, potential insights from platforms such as Web of Science, Google Scholar, PsycINFO, and ProQuest may not have been captured. Additionally, the selection of articles may be subject to inherent biases despite the established inclusion criteria. Future research should aim to incorporate a broader and more diverse range of databases and include empirical data to validate and extend the current findings. Adopting a more integrative and multifaceted research approach will further enhance the generalizability and depth of understanding regarding the interplay between organizational identification, workaholism, and burnout.

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Organizational identification, workaholism, and burnout: a cross-sectional study of age, gender, tenure, and work arrangements

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Abstract. This study investigates the relationships between organizational identification (OI), workaholism, and burnout among employed individuals in Latvia, with a focus on how gender, age, and tenure moderate these relationships. Data were collected from May 29 to October 27, 2024, using the QuestionPro platform, resulting in 954 total responses, of which 879 were completed (completion rate: 92.14%). The results demonstrate that high OI significantly predicts burnout ($\beta = 1.167$, $p = 0.002$), particularly when combined with workaholism ($\beta = 2.045$, $p = 0.001$). Employees exhibiting both high OI and workaholism reported the highest levels of burnout. A negative association between tenure and burnout ($\beta = -1.3419$, $p = 0.020$) suggests that experienced employees develop better coping strategies. Gender differences were also observed: women in the high OI group reported significantly higher burnout levels ($\beta = 2.2538$, $p = 0.045$), whereas women in the low OI group experienced lower burnout levels ($\beta = -3.2624$, $p = 0.020$). These findings highlight the complex interplay between organizational identification, workaholism, and burnout, emphasizing the need for organizational interventions targeting workaholism and gender-specific challenges. Future research should further explore the impact of cultural and organizational factors in shaping these dynamics.

Key words: burnout, organizational identification, workaholism, stress, gender, tenure, age.

INTRODUCTION

The interplay between organizational identification (OI), workaholism, and burnout has been a critical focus in organizational psychology (Caprar et al., 2022; Dunning et al., 2024; Filippi et al., 2024; Presbitero & Aruta, 2024; Teresi et al., 2024). Organizational identification refers to the extent to which employees align their self-concept with the values, goals, and mission of their organization (Ashforth & Mael, 1989). High levels of OI are generally linked to positive outcomes, including increased job satisfaction, loyalty, and performance (Mael & Ashforth, 1992). However, recent research suggests that while OI drives workaholism, it does not always result in burnout, indicating that additional factors moderate this relationship (Caprar et al., 2022). This paradox remains an area of ongoing inquiry, with emerging evidence suggesting that individual and organizational factors, including age, gender, tenure, and work arrangements, may play a crucial role in determining whether strong organizational identification results in burnout. Thus, exploring these moderating factors is essential to understanding the complexities of the OI-workaholism-burnout relationship.

How organizational identification drives workaholism

Organizational identification is a key motivator for employee behavior, as it creates a sense of belonging and attachment to the organization (Ashforth & Mael, 2024). Employees who identify strongly with their organization may work excessively to contribute to its success, which can lead to workaholism - characterized by an uncontrollable urge to work long hours at the expense of other life domains (de Beer et al., 2022). This excessive dedication stems from employees' internalization of organizational values, leading them to prioritize professional commitments over personal well-being.

High OI fosters this compulsive need to work, as employees may internalize the organization's values and perceive its success as a reflection of their own worth (Ashforth & Mael, 2024). Research has shown that employees with high OI are often driven to meet organizational expectations, which can result in excessive work behaviors, even when those behaviors are not always rewarded by the organization (Mazzetti et al., 2023). Furthermore, in organizations with a strong performance-driven culture, employees with high OI may feel compelled to work excessively to align with perceived expectations, further reinforcing workaholic behaviors. This dynamic underscores the paradox: OI fosters workaholism but does not necessarily result in burnout (Caprar et al., 2022).

The key question arises - why does organizational identification drive workaholism without consistently leading to burnout? Demographic factors such as age, gender, tenure, and work arrangements may provide insights into why this occurs, and exploring these variables may help explain the observed discrepancy in the relationship between OI, workaholism, and burnout.

How age moderates the relationship between organizational identification, workaholism, and burnout

Age plays a significant role in how organizational identification influences workaholism and burnout. Younger employees may have a stronger desire to prove themselves within the organization, making them more susceptible to workaholism as they strive to meet organizational standards (Ng & Feldman, 2010). As a result, they may internalize organizational values more deeply and engage in excessive work behaviors, driven by a sense of obligation to demonstrate their commitment. However, this same group may also face higher risks of burnout due to limited coping resources and lack of experience in managing work demands (Muteshi et al., 2024). On the other hand, older employees may have developed more effective coping strategies and may be less likely to experience the compulsive need to overwork despite high organizational identification. They may focus more on work-life balance or have a clearer sense of boundaries between their professional and personal lives (Zwack & Schweitzer, 2013). Additionally, older employees may be more selective in how they engage with work, using strategies such as task prioritization and delegation to reduce stress while maintaining high OI. This could protect them from the negative effects of workaholism, even if they strongly identify with their organization. Furthermore, as Waligóra (2024) highlights, age-inclusive HR practices can buffer the effects of workaholism by providing targeted resources that support both younger and older employees' well-being. Thus, the relationship between organizational identification and burnout may be moderated by age, with younger employees being more vulnerable to burnout due to their workaholic tendencies, while older employees benefit from experience and supportive HR practices in managing work demands.

How gender shapes the link between organizational identification, workaholism, and burnout

Gender also influences the way OI impacts workaholism and burnout. Gendered expectations in the workplace can shape how employees with high OI behave. For instance, women often face higher levels of work-life conflict, especially when they identify strongly with an organization that prioritizes long working hours and high commitment (Muteshi et al., 2024). This added pressure can exacerbate workaholism, as women may feel compelled to meet both organizational expectations and traditional caregiving roles outside of work. In contrast, men may experience different pressures where organizational success is closely tied to their professional identity. Men with high OI may engage in workaholism due to societal expectations that equate professional success with personal worth. High OI can lead to workaholism as men might feel an intense need to meet organizational goals at the expense of personal life, but they may not face the same work-life conflict as women (Akçakese et al., 2024). The impact of OI on burnout can also vary across genders, as women may experience higher burnout rates due to greater work-life conflict and societal pressures, while men may face burnout due to the stress of overwork and the pressure to maintain high performance. These gendered experiences highlight how demographic factors shape the relationship between OI, workaholism, and burnout.

The role of tenure in mitigating the effects of workaholism on burnout

Tenure, or the length of time an employee has been with an organization, can influence the effects of OI on workaholism and burnout. Employees with longer tenure often have a stronger sense of organizational commitment and identity (Porter et al., 2024). However, this stronger identification may not necessarily lead to workaholism. Long-tenured employees may have developed a deeper understanding of balancing work with personal life, and they may be more adept at managing their work hours and responsibilities (Caines & Treuren, 2024). In contrast, employees with shorter tenure may still be in the process of socializing into the organization and may feel a stronger need to demonstrate their loyalty through overwork, increasing their susceptibility to workaholism. Employees with shorter tenure may also be at greater risk of burnout if they have not yet established the coping mechanisms or resources needed to manage high job demands. Their eagerness to prove themselves, combined with a lack of experience in handling organizational pressures, could lead to both workaholism and burnout, especially if the organizational culture supports overwork as a measure of commitment. Tenure may, therefore, play a moderating role in the relationship between OI, workaholism, and burnout.

Work arrangements as a buffer against workaholism and burnout

Work arrangements, including remote work and flexible work hours, have increasingly become a significant factor in shaping the relationship between OI, workaholism, and burnout. Remote or flexible work arrangements can blur the boundaries between work and personal life, making it more difficult for employees to disengage from work and take necessary breaks (Mazzetti et al., 2023). Employees with high OI may be particularly vulnerable to this, as they may feel compelled to continue working beyond standard hours to prove their commitment to the organization, especially when their work is not subject to the usual time and space boundaries of an office environment. However, work arrangements may also have protective effects, particularly if they offer employees greater autonomy and control over their schedules. For example, employees working in environments that promote work-life balance and provide autonomy may be able to engage in high levels of work without experiencing burnout, as they can set their own boundaries and manage their work demands more effectively (Schaufeli et al., 2020; Bakker & Demerouti, 2024). Flexible work arrangements may allow employees to maintain high organizational identification and engagement while mitigating the risks of burnout (Geidelina-Lugovska & Cekuls, 2023), provided they have the support and resources necessary to maintain balance.

The role of demographic factors in the workaholism-burnout paradox

While organizational identification often leads to workaholism, it does not always result in burnout. Demographic factors such as age, gender, tenure, and work arrangements can provide valuable insights into why this paradox exists. Age and gender may influence how strongly employees feel the need to align their personal identity with organizational values, affecting both their likelihood of engaging in workaholic behaviors and their susceptibility to burnout. Employees with longer tenure may have developed the skills to manage their work demands more effectively, while those with shorter tenure may feel more compelled to overwork. Similarly, work arrangements, especially flexible or remote work, can either exacerbate or mitigate the effects of workaholism on burnout, depending on the support structures and autonomy available to employees.

The relationship between organizational identification, workaholism, and burnout is complex and influenced by several demographic factors, including age, gender, tenure, and work arrangements. While high OI can lead to workaholism, the risk of burnout is not a guaranteed outcome. Age and gender differences, along with the length of time an employee has been with an organization and their work arrangements, all play crucial roles in determining whether workaholism leads to burnout. Understanding these demographic influences is essential for developing strategies that can help mitigate the risks associated with strong organizational identification, enabling organizations to foster healthy, engaged employees without compromising their well-being.

This study seeks to clarify the complex interplay between OI, workaholism, and burnout by examining the role of demographic and workplace factors. By investigating these relationships, this study contributes to the ongoing discussion on sustainable work practices and provides practical insights for organizations aiming to balance employee commitment with well-being. Understanding how to foster healthy organizational identification - where employees remain engaged without succumbing to workaholism or burnout - can inform policies that enhance both productivity and well-being in modern workplaces.

MATERIALS AND METHODS

Data Collection

Data for this study were collected between May 29, 2024, and October 27, 2024. The target population consisted of employed individuals in Latvia, estimated to be 889,900 in 2023 (OSP, NBL020 database). The sample included 954 respondents, who were recruited through the QuestionPro platform. Participants completed an online survey assessing various workplace-related factors, including organizational identification, workaholism, and burnout.

The survey received a total of 976 views, and the response rate was high, with 954 total responses recorded. After cleaning the data, a final sample of 879 completed was included in the analysis. This represents 92% of the surveys that were started. Of the respondents, 63 surveys were marked as incomplete (with partial responses), and 12 responses were terminated due to technical issues or other non-response reasons. When considering the number of participants who actually viewed the survey, the completion rate drops slightly to 90% of the views, while the rate of responses completed relative to those who started the survey was notably higher, at 98%. Table 1 represents survey participation overview.

Table 1. Survey participation overview

Survey stage	Number/Percentage
Viewed	976
Started	954
Completed	879
Viewed/started	98%
Viewed/completed	90%
Started/completed	92%

Source: Author's compilation based on collected survey data.

These statistics demonstrate a high level of engagement and completion, ensuring that the dataset provides a robust basis for analysis. The gender distribution of respondents is 57% male and 43% female. Table 2 presents the distribution of respondents across different age groups.

Table 2. Distribution of respondents by age group

Age group	Amount of respondents	Share, %
15–24 years old	49	6%
25–34 years old	195	22%
35–44 years old	205	23%
45–54 years old	182	21%
55–64 years old	205	23%
65–74 years old	43	5%
TOTAL	879	100%

Source: Author's compilation based on collected survey data.

The data was gathered from a diverse group of employed individuals, allowing for valuable insights into the dynamics of organizational identification, workaholism, and burnout among workers in Latvia.

Data cleaning and preprocessing

Before conducting the analyses, we performed initial data cleaning by checking for missing values in key variables. Rows with missing data were removed, resulting in a final sample of 868 observations. Variables related to OI, workaholism, burnout, age, gender, tenure, and work arrangements were retained for analysis.

Grouping by organizational identification (OI)

To better understand the impact of OI on workaholism and burnout, the sample was split into two groups based on the median value of OI (35.00). Respondents with scores above the median were categorized as the high OI group, while those below the median formed the low OI group. The distribution of OI scores shows a left-skewed pattern, indicating that most respondents identify strongly with their organization, while fewer report very low OI levels. This suggests that the median split does not reflect two naturally distinct groups but rather provides a statistically balanced way to compare individuals with relatively higher and lower OI levels. Alternative grouping methods, such as quartile-based classification, were considered but were not implemented to maintain group comparability and statistical power.

Descriptive statistics

The descriptive analysis revealed the following key insights:

- High organizational identification group. This group exhibited higher mean levels of workaholism and burnout, suggesting that employees with strong identification with their organization tend to work excessively and experience more burnout.
- Low organizational identification group. Employees with lower OI exhibited lower mean levels of workaholism and burnout, indicating that reduced organizational identification may be associated with less workaholic behavior and lower burnout risks.

Statistical analysis confirmed that these differences are significant. Independent *t*-tests showed that the high organizational identification group exhibited significantly higher workaholism ($t = 19.02$, $p < 0.001$) and burnout ($t = 19.78$, $p < 0.001$) levels compared to the low organizational identification group. These findings suggest that stronger organizational identification is associated with increased work intensity and emotional exhaustion.

These descriptive analyses provide a foundational understanding of the study sample, highlighting key demographic variables and their potential influence on the relationships among organizational identification, workaholism, and burnout. With a clear distinction between high and low OI groups, the subsequent analyses explore the impact of these factors on employee well-being. The following section presents the regression results, shedding light on how demographic variables and work behaviors contribute to burnout.

RESULTS AND DISCUSSION

Regression and moderation analyses were conducted to further examine the relationships between organizational identification, workaholism, and burnout. These models assess how demographic factors - age, gender, tenure, and work arrangements - moderate the effects of OI and workaholism on burnout. The results provide critical insights into the conditions under which high OI leads to increased burnout risks and the extent to which workaholism exacerbates these effects.

Regression Analysis

Separate regression analyses were conducted for the high OI and low OI groups to assess the relationships between OI, workaholism, and burnout. Burnout was the dependent variable, and the independent variables included OI, workaholism, age, gender, tenure, and work arrangements.

The regression model for the high OI group indicated that both OI (coef = 1.1670, $p = 0.002$) and workaholism (coef = 2.0450, $p < 0.001$) were significant positive predictors of burnout. This suggests that employees who strongly identify with their organization and engage in workaholic behaviors are at a higher risk of burnout. Tenure was negatively associated with burnout (coef = -1.3419, $p = 0.020$), indicating that longer tenure within the organization is associated with reduced burnout. Additionally, gender was found to have a significant positive effect (coef = 2.2538, $p = 0.045$), suggesting that female employees in the high OI group may experience higher levels of burnout compared to their male counterparts.

In the low OI group, both OI (coef = 0.6581, $p < 0.001$) and workaholism (coef = 1.2589, $p < 0.001$) were still significant predictors of burnout, though the effect sizes were smaller compared to the high OI group. Gender had a negative impact on burnout in this group (coef = -3.2624, $p = 0.020$), suggesting that female employees in the low OI group tend to experience lower levels of burnout. Tenure also showed a significant negative relationship with burnout (coef = -1.4780, $p = 0.017$), similar to the high OI group.

Moderation Analysis

To explore whether gender moderated the relationship between OI and burnout, as well as the relationship between workaholism and burnout, we conducted interaction analyses by creating interaction terms between OI and gender, and between workaholism and gender.

The interaction term between OI and gender (coef = 0.1743, $p = 0.249$) was not significant, suggesting that gender does not significantly moderate the relationship between OI and burnout.

The interaction term between workaholism and gender (coef = 0.2434, $p = 0.121$) was also not statistically significant, although the effect was marginally positive. This suggests that while gender may influence the relationship between workaholism and burnout, the effect is not strong enough to reach statistical significance.

These findings suggest that organizational identification and workaholism play a crucial role in predicting burnout, but gender can influence the strength and direction of these relationships.

Fig. 1 presents the conceptual model illustrating the relationships between organizational identification, workaholism, burnout, gender and tenure. The model is based on the statistical findings from the study and provides a visual representation of the key relationships identified in the regression analysis.

This conceptual model serves as a theoretical foundation for understanding how demographic and work-related factors influence the OI-workaholism-burnout relationship, providing insights into potential intervention strategies aimed at mitigating burnout risks in organizational settings.

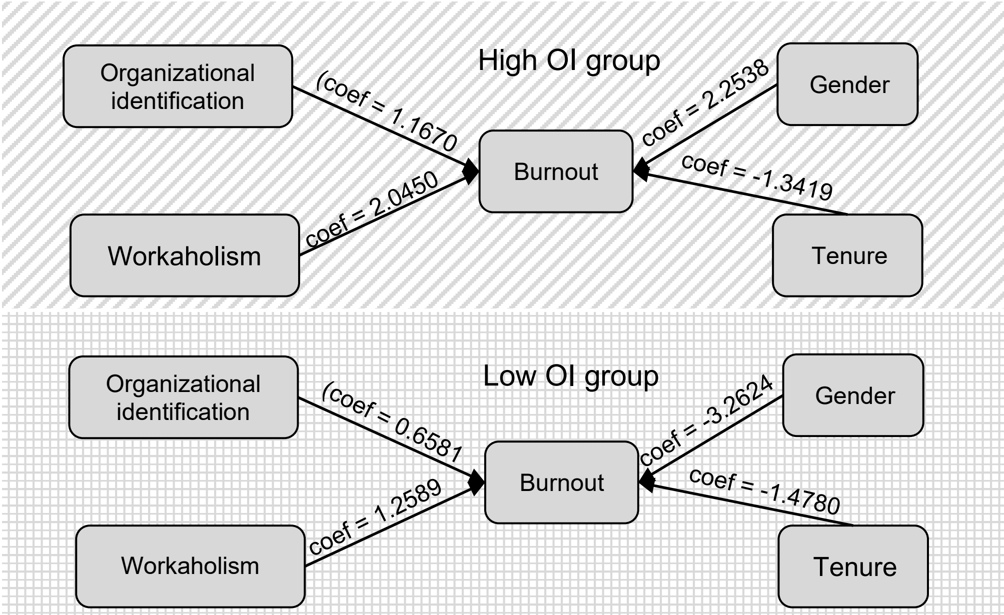

Figure 1. Conceptual model of organizational identification, workaholism, burnout, gender and tenure with regression values.

The data analysis yielded several key findings regarding the relationships between organizational identification (OI), workaholism, and burnout. These findings have important implications for understanding employee well-being in organizational settings. They align with and expand upon the existing literature on these constructs while offering new insights into the moderating role of gender.

Our analysis revealed that employees with high OI are more likely to experience burnout, particularly when they also exhibit workaholism. This finding is consistent with recent studies suggesting that strong organizational identification may contribute to workaholism (Caprar et al., 2022; Dadaboyev et al., 2023), leading to negative outcomes such as burnout. Specifically, employees who internalize organizational values and goals to an extreme may feel compelled to overwork, aligning with Schaufeli et al.'s (2008) finding that workaholism often arises from an obsessive need to meet organizational demands, thus leading to increased stress and burnout. In high-commitment environments, this psychological identification can intensify the pressure to succeed, exacerbating feelings of burnout.

Consistent with the literature, workaholism was found to be a strong and consistent predictor of burnout across both high and low OI groups. This finding underscores the well-established link between excessive work and emotional exhaustion (Andreassen et al., 2018). The stronger relationship observed in the high OI group aligns with Taris et al. (2020), who suggested that employees with strong organizational identification are more likely to exhibit workaholic behaviors and, in turn, suffer from higher levels of burnout due to their inability to disengage from work demands. This aligns with the broader perspective that workaholism, when left unchecked, leads to negative health and well-being outcomes, including burnout.

The analysis revealed distinct gender effects: in the high OI group, women reported higher levels of burnout, whereas in the low OI group, women reported lower levels of burnout. While the literature highlights gendered experiences in the workplace, this finding contributes to understanding how organizational context (i.e., high vs. low OI) can shape gendered experiences of burnout (Liu et al., 2024). In high OI environments, the pressure to perform may be exacerbated for women, especially in cultures where overwork is rewarded, leading to higher stress and burnout. Gendered expectations in the workplace, as suggested by Morkevičiūtė & Endriulaitienė (2022), could explain why women with high OI feel a stronger need to demonstrate their commitment, which can, in turn, heighten their burnout risk. In contrast, women in organizations with lower OI may not experience the same pressures, potentially reducing their burnout levels.

Our findings also suggest that longer tenure is associated with lower burnout levels, aligning with prior research (Varol et al., 2021), which posited that more experienced employees develop better coping strategies and have more resources to manage work stress. This is particularly relevant in high-OI organizations, where the intense identification with the organization could otherwise amplify stress. Tenure allows employees to acclimatize to organizational demands and to find ways to balance work and personal life, thus mitigating burnout over time.

These findings contribute to the growing body of literature on organizational identification, workaholism, and burnout by emphasizing the role of gender and tenure in shaping the strength of these relationships.

Avanzi et al. (2012) support that highly identified employees may work intensively to achieve organizational goals, but an excessive attachment can lead to workaholism, where over-identified employees may underestimate job demands, overestimate their coping abilities, and spend excessive time working, ultimately compromising their psychological well-being and health due to insufficient recovery time. Our results reinforce this by showing that high-OI employees experience higher burnout, particularly when workaholism is present. However, our findings also extend Dadaboyev et al.'s (2023) research by demonstrating that gender plays a significant role, particularly in high-OI contexts where female employees experience heightened burnout.

Andreassen et al. (2018) and Schaufeli et al. (2009) strongly support workaholism as a predictor of burnout. Both highlighted the negative effects of excessive work on employee health. Our analysis provides further evidence that workaholism remains a robust predictor of burnout across organizational contexts, with the strongest effects in organizations where employees report high levels of organizational identification.

Ramos et al. (2016) discussed the role of tenure in moderating burnout, finding that younger employees with longer tenure are more vulnerable to burnout due to increased job demands, while older employees, especially those in managerial roles, exhibit greater resilience. Our findings confirm this by showing that tenure negatively correlates with burnout, suggesting that more experienced employees are better equipped to manage organizational stressors, particularly in high-organizational identification (OI) contexts.

These findings suggest that organizational identification can have both positive and negative effects on employee well-being. While it fosters commitment and engagement, it may also increase the risk of workaholism and, consequently, burnout. This study highlights that workaholism is a key driver of burnout and that demographic and work-related factors, such as age, gender, tenure, and work arrangements, shape these relationships in different ways.

From an organizational perspective, these results underscore the need for strategies that balance strong employee commitment with well-being initiatives. Organizations should consider interventions such as clear work boundaries, flexible work arrangements, and mental health support programs to reduce the negative effects of workaholism and burnout.

While this study provides valuable insights, further research should examine the cultural and contextual factors that may influence these relationships. Future studies could explore how organizational culture, leadership styles, and job resources impact the dynamics of OI, workaholism, and burnout, particularly in cross-cultural settings. Additionally, investigating how individual factors and resilience moderate these relationships could provide a deeper understanding of how employees with varying characteristics respond to organizational demands.

CONCLUSIONS

This study explored the relationships between organizational identification, workaholism, and burnout, considering the moderating effects of age, gender, tenure, and work arrangements. The findings suggest that organizational identification can be both beneficial and detrimental, as it fosters strong commitment and motivation but may also encourage workaholic tendencies, which in turn contribute to burnout.

The results highlight the importance of individual and work-related factors in shaping burnout risk. Employees with longer tenure may develop coping strategies that protect against burnout, while younger employees may be more vulnerable due to higher work demands and fewer established resilience mechanisms. Gender differences suggest that women in highly identified roles may experience greater work-life conflict, making them more susceptible to burnout. Additionally, work arrangements, particularly flexible options, may play a crucial role in moderating these effects by allowing employees to manage workload pressures more effectively.

From a practical perspective, organizations should focus on creating supportive work environments that maximize the benefits of organizational identification without fostering excessive work engagement. Strategies such as promoting work-life balance, discouraging overwork, and offering tailored well-being initiatives can help mitigate burnout risks while maintaining employee engagement and productivity.

Future research should further investigate the long-term effects of organizational identification on well-being, as well as the role of cultural and organizational contexts in shaping these relationships. A deeper understanding of these dynamics can help organizations develop more sustainable and employee-centric work cultures that balance commitment, performance, and well-being.

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Sensory assessment and consumer acceptability of confectionery products made with pine cones

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Abstract. The non-timber part of the forest includes mushrooms, berries, cones, shoots etc. The aim of this study was to evaluate consumer acceptability of confectionery products made with pine cones. For the study two pine cone syrups using osmosis were prepared: pine cone syrup with white sugar (PSW) and pine cone syrup with brown sugar (PSB). Four jams were prepared: apple - pine cone jam without added sugar (AC), pine cone jam with white sugar (CW), pine cone jam with brown sugar (CB), and pine cone jam with stevia (CS). Also, four gummy candies were prepared using different thickeners - gelatine (CG), pectin HM (CpHM), pectin LM (CpLM), and agar - agar (CA). To all products sensory evaluation was performed. In total 23 participants participated in this study. The results showed that the PSW had the most intense colour, aroma, taste, and aftertaste, the sweetness in both syrups was the same. The obtained data for jams showed that the CB and AC was the most pleasant in terms of colour, while the CB and CS was the most pleasant in terms of consistency. For the gummy candies' colour and texture, the highest rated were CpHM. However, for the aroma, taste and aftertaste, the highest acceptance was found in CG. In conclusion, healthier confectionery products with reduced sugar content can be effectively developed by using a non-timber forest resource such as pine cones. This approach allows manufacturers to create confectionary products that satisfy consumer demand for enjoyable sweetness while addressing health concerns.

Key words: gummy candies, intensity test, jams, JAR test, stevia.

INTRODUCTION

Nowadays, people care about a healthy diet, and natural foods are in demand. Natural foods contain many nutrients and are considered 'healthy' (Nabi et al., 2023). The terms 'natural' and 'healthy' are among the most commonly used terms in food marketing. Traditional foods have increased their sales by labeling with the words natural and healthy (Asioli et al., 2017). Sugar is mainly used in food as a sweetener and preservative, and in syrups and jams, it is used to improve viscosity (White, 2018). Sugar is also needed in gummy candies, where pectin is added as a thickener. Gummy candies with lower sugar content can be made if agar-agar or gelatin is used instead of pectin (Vojvodič Cebins et al., 2024). White sugar, which contains 99% sucrose, is used in confectionery, while brown cane sugar contains only 88–93% sucrose, depending on where the sugar cane is grown. Brown sugar is often considered healthier than white sugar. The molasses in brown sugar can affect and alter the taste and aroma of the product (Azlan et al., 2020). Low- calorie sweeteners can be considered as a substitute for sugar. Low - calorie sweeteners allow consumers to choose foods and beverages with different calorie content and sweetness. Sweeteners such as acesulfame K, aspartame and stevia are 50 to 600 times sweeter than sucrose, while neotame is 7,000 to 13,000 times sweeter than sucrose. Stevia (*Stevia rebaudiana (Bert.)*) is a natural sweetener, and due to its origin, it is considered the safest sweetener (Abdullah et al., 2014). With the growing interest in the use of sweeteners in fruit products, such as jams, concerns about changes in taste and texture are growing. Consumers are aware of sugar reduction and substitution, but there is a lack of understanding of how the taste and texture of jams change. Jam is a food product obtained mainly by boiling fruit pulp with sugar, sometimes also adding pectin, citric acid, and preservatives (Uribe-Wandurraga et al., 2021). In jams, sugar can be replaced with a sweetener - stevia. Stevia is resistant to acid and heat, so it is a good alternative to sugar (Nourmohammadi et al., 2021). Trees of the genus *Pinus* are among the most widespread trees in the world. Pines are used for their wood, resin, and nuts, while needles are mainly processed into extracts due to their high antioxidant activity and bioactive compounds (Xu et al., 2012). Pine cones, like other coniferous products, are rich in phenolic acids and flavonoids, which have beneficial effects, as well as antioxidant properties (Ferreira-Santos et al., 2020). In some parts of Asia, pine needles, cones, and pine pollen are used in food and as dietary supplements. Traditionally, syrups and tea were made from pine cones, but today their use can be expanded to e.g. in jams, desserts, etc. (Karklina & Ozola, 2023a). In Latvia, the use of stevia in food is in accordance with EU Regulation 2021/1156, in which stevia is indicated as stevia glycoside and designated as E960a. Stevia glycoside can be used in jams, gummy candies, chapter 04.2.5.2 of the regulation describes their use. The maximum permitted amount is indicated as 200 mg kg^{-1} (Commission Regulation (EU) 2021/11515). However, the Latvian Food and Veterinary Service (PVD) monitors food safety and regulation in Latvia. According to the PVD, if a product does not contain pine cone pieces, then the product is classified as a food, but if it contains pine cone pieces, it is classified as a food supplement, taking into account the health benefits of pine cones (MK No. 2015/685). Adding pine cones to products increases the value of the product itself. According to the regulations of the Cabinet of Ministers No. 2015/685, pine cones have health benefits that can positively affect human health. The aim of this study was to evaluate consumer acceptability of confectionery products with reduced sugar content made with pine cones.

MATERIALS AND METHODS

The research was carried out in the laboratories of the Food Institute at the Latvia University of Life Science and Technologies for the development of pine cone confectionery products: syrups, jams and gummy candies. Green pine cones harvested from Scots pine (*Pinus sylvestris*) were used to prepare the confectionery. The pine cones were harvested in a private forest area near Riga, Latvia in June 2022. The green pine cones were stored in high-density polyethylene (HDPE) plastic bags in a freezer at -20 ± 2 °C until further use.

The syrup is prepared using:

- white sugar Dansukker 'Jelgavas cukurs' producer A/S Nordic sugar (Sweden), country of origin Lithuania;
- brown sugar Dansukker 'Demerara', producer A/S Nordic sugar (Sweden), country of origin Malawi.

For pine cone jams used:

- white and brown sugar mentioned before);
- LM pectin with calcium salts 'Sosa', producer Sosa (Spain);
- sweetener Alvo stevia, producer UAB Pajuva (Lithuania).

For preparation of gummy candies used:

- pine cone pieces remaining after syrup preparation;
- LM pectin (mentioned before);
- citrus HM pectin for jelly moulds 'Sosa', producer Sosa (Spain);
- edible gelatin 'Rimi', country of origin Lithuania;
- agar - agar produced in Italy;
- spruce sprout juice, produced by slow rotation juicer sprouts of *Norway Karst L* according to (Karklina, Ozola, Ibrahim, 2024; Karklina, 2024) method;
- and pine cone syrup with brown sugar were also used, based on pectin recommendations (Sosa pectins) and physical parameters of pine cone syrups according to (Karklina & Ozola, 2023a).

The methods for the preparation of each product are detailed below.

Preperation of pine cone syrups

Pine cone syrups were prepared by osmosis according to the method of (Karklina & Ozola, 2023a). The prepared syrups were stored in glass jars at room temperature of 20 ± 2 °C until further use. The prepared syrups were represented in Fig. 1.

Pine cone syrups did not contain pieces of pine cones. Pine cone pieces as a by-product were frozen and used for gummy candy preparation.

PSW PSB

Figure 1. Prepared pine cone syrups. Pine cone syrup with white sugar (PSW) and pine cone syrup with brown sugar (PSB).

Preparation of pine cone jams

Regardless of the method of preparation of pine cone jam, the cones were initially blanched for 5 minutes at 80 °C. Blanching is necessary to soften the pine cones. Unprocessed pine cones can be fibrous. Blanching helps to release resin-forming compounds, thus improving the taste of the jam (Boutenko, 2013). Pine cone jams were prepared according to the method of (Karklina & Ozola, 2023b). The materials used and the amounts of jam are indicated in Table 1, all prepared pine cone jams were stored at a room temperature of 20 ± 2 °C until further use. Prepared jams represented in Fig. 2.

AC CB CW CS

Figure 2. Prepared pine cone jams. Pine cone apple jam without added sugar (AC), pine cone jam with brown sugar (CB), pine cone jam with white sugar (CW), and pine cone jam with stevia (CS).

Table 1. Ingredients used for pine cone jam are listed in g per 100 g volume

Pine cone jam type	Pine cones	Water	Apple juice	White sugar	Brown sugar	Stevia	Pectin
Pine cone apple jam	10.0	-	90.0	-	-	-	-
Pine cone jam with brown sugar	10.0	45.0	-	-	45.0	-	-
Pine cone jam with white sugar	10.0	45.0	-	45.0	-	-	-
Pine cone jam with stevia	10.0	45.0	-	-	-	2.0	2.0

Preparation of pine cone - apple jam (AC), used quantities of ingredients mentioned in Table 1

After blanching, the green pine cones were chopped into smaller pieces and boiled in apple juice for two hours until a smooth, flowing mass was formed. The resulting mass was poured into clean, sterilized 250 g glass jars and sealed. The filled jars were stored for further analysis.

Preparation of pine cone jam with brown (CB) and white sugar (CW), used quantities of ingredients mentioned in Table 1

In jams made with sugar, pectin was not added because sugar is able to create the necessary jelly-like consistency for the jam. According to (Garcia- Garcia et al., 2018), pine cones also contain pectin, but their concentration is significantly smaller compared to apples. The process begins in the same way as making pine cone-apple jam. The pine cones are first blanched and then cut into smaller pieces. The pine cones are boiled in water for an hour. Then sugar (brown or white) is added and the mixture is kept on a hot stove until the sugar dissolves, forming a smooth, flowing mass. The resulting mass is then poured into clean, sterilized 250 g glass jars and sealed. The filled jars are stored until further analysis.

Preparation of pine cone jam with stevia (CS), used quantities of ingredients mentioned in Table 1

LM pectin was used to make stevia jam. According to the pectin specification (Sosa pectin's), LM pectin is more suitable for low-sugar and sugar-free jams because it works synergistic with calcium, unlike HM pectin, which relies on high sugar content to form a gel. The water and pine cones were boiled for an hour. Then the stevia and LM pectin were mixed and added to the water and pine cone mixture. The mixture was kept on a hot stove and stirred until the stevia and pectin dissolved, obtaining a smooth, flowing consistency. The resulting mass was then poured into clean, sterilized 250 g glass jars and sealed. The filled jars are stored until further analysis.

Preparation of pine cone gummy candies

Certain volatile compounds that give a more resinous pine aroma are more intense in pine cone syrup than in spruce sprout juice. Therefore, no spruce sprout juice was added to the candies in which pine cone syrup was added (Karklina & Ozola, 2023a; Karklina, 2024) (see Results and Discussion section Fig. 7, B).

Method with gelatin

To prepare pine cone candies with gelatin (CG), the ingredients listed in Table 2 were used. Water was mixed with sugar, pine cone pieces, spruce sap, gelatin, and citric acid. The gelatin mixture was allowed to ripen for 10 minutes. Once the gelatin had ripened, the mixture was stirred and heated to 100 °C. The finished mixture was then poured into molds and left to harden at room temperature of 20 ± 2 °C for 12 hours (h). The prepared gummy candies were stored in polyethylene (PE) bags in the refrigerator until further use.

Table 2. Ingredients used for pine cone gummy candies are listed in g per 100 g volume

Gummy candy	Drinking water	White sugar	Pine cone piecies	Pine cone syrup	Spruce sprout juice	HM pectin	LM pectin	Citric acid	Gelatine	Agar-agar
Gummy candy with gelatine	53.0	20.0	10.0	-	2.0	-	-	1.0	4.0	-
Gummy candy with HM pectin	18.0	18.0	10.0	40.0	-	3.0	-	1.0	-	-
Gummy candy with LM Pectin	30.0	35.0	10.0	19.0	-	-	1.0	1.0	-	-
Gummy candy with agar - agar	45.0	26.0	10.0	-	2.0	-	-	-	-	2.0

Method with HM pectin

To prepare pine cone candies using HM pectin, the ingredients listed in Table 2 were used. The liquid and dry ingredients were weighed separately. The pectin, citric acid and sugar were mixed together and then added to the cold liquid mixture. The product was stirred and gradually heated until it reached boiling point over low heat. Pine cone syrup and pine cone pieces were added during boiling and the mixture was kept boiling for another 10 minutes. The finished mixture was then poured into molds and left to harden at room temperature of 20 ± 2 °C for 12 h. The prepared gummy candies were then stored in polyethylene (PE) bags in the refrigerator until further use.

Method with LM pectin

To prepare pine cone candies using LM pectin with calcium salts (CpLM), the ingredients listed in Table 2 were used. First, the liquid and dry ingredients were weighed separately. The dry ingredient mixture was added to the liquid mixture. The mixture was allowed to swell for 5 minutes and then the combined mixture was heated over low heat, stirring continuously, until it boiled. Continue to boil for 5 minutes. The finished mixture was then quickly poured into molds and allowed to set at room temperature of 20 ± 2 °C for 12 h. After setting, store the gummy candies in polyethylene (PE) bags in the refrigerator until ready to use.

Method with agar - agar

To prepare pine cone candies using agar-agar, the ingredients used are listed in Table 2. The liquid and dry ingredients are mixed separately. The dry ingredient mixture is added to the liquid mixture. The mass was stirred and boiled for 5 minutes at 100 °C. The finished mass was poured into molds and left to harden at room temperature of 20 ± 2 °C for 12 h. After hardening, the gummy candies were stored in polyethylene (PE) bags in the refrigerator until further analysis.

Sensory evaluation of pine cones of confectionery products

Products made using pine cones are specific products with a special taste and smell, so a different evaluation method was chosen for each product. The method was chosen to determine consumer acceptance, for example, an intensity scale test to determine the intensity of the syrup properties (color, sweetness, pine aroma) and to explain in the comments which of the samples they found more acceptable based on the intensity. An arrangement test, in which the jams had to be arranged in order of liking based on different jam properties. And the Just About Right (JAR) test to conclude, by the acceptability, which characteristic seems just about right. All prepared pine cone confectionery products were evaluated using sensory analysis. A total of 23 trained panelists, 22 women and 1 man, all aged 20–22 years, participated. They were students from the Food Institute of the Faculty of Agriculture and Food Technology of the Latvian University of Life Sciences and Technology. The methods used for the sensory evaluation of each product are described in more detail below. The sensory evaluation of pine cone syrups was evaluated according to (Majore & Cipriviča, 2023; Karklina & Kampsue, 2021) with minor modifications. Participants were asked to evaluate the color intensity, aroma, sweetness, pine flavor, and aftertaste. Example of intensity scale, represented in Fig. 3.

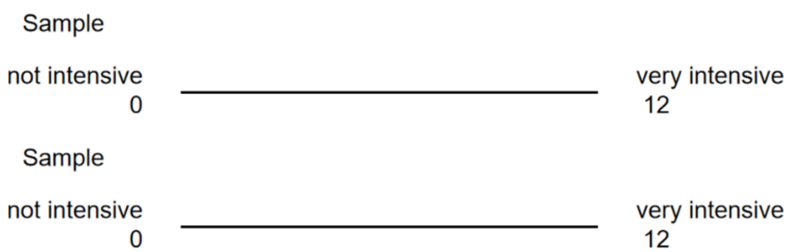

Figure 3. Authors example of a linear intensity scale according to the standard method (DLG, 2010).

A 12 cm Intensity scale was used, where 0 could be described as not intense and 12 as very intense. After the sensory evaluation, consumers were given the opportunity to comment on why the product seemed more acceptable in terms of intensity. The comments were taken into account.

The sensory evaluation of pine cone jams was assessed according to ISO 8589:2007. Participants were asked to rank the jam samples (Fig. 4) from 1 to 4 (1 – least acceptable; 4 – most acceptable) according to their color, taste and consistency.

Properties	Pine cone jams			
	AC	CB	CW	CS
Colour				
Consistency				
Taste				

Figure 4. Authors made an example of pine cone jam arrangement test according to the standard method (ISO 8589:2007).

After the sensory evaluation, consumers were asked to comment on which aspects of the product they accepted based on specific characteristics. Their comments were taken into account.

The sensory evaluation of pine cone candies was carried out according to (Karklina & Ozola, 2024b). Participants rated the gummy candies using the Just About Right (JAR) test, assessing their appearance, aroma, texture and aftertaste. Each parameter was rated as follows: –1 for too little, 0 for almost right and 1 for too much. After this evaluation, consumers were asked to comment on which product they found most acceptable. These comments were also considered.

Statistical analysis

The sensory evaluation aimed to compare the intensity of pine cone syrups, the acceptance of pine cone jam by arrangement test, and the Just About Right (JAR) test for pine cone gummy candies. The pine cone syrups' mean was calculated using WPS Office 2023. A two-way factorial *ANOVA* was also performed on the results to detect significant differences at a significance level of ($p \leq 0.05$). The mean was calculated for the pine cone jam acceptance test, and the data were presented as percentages. The JAR test for pine cone gummy candies was conducted, and the results are also displayed as percentages. WPS Office 2023 was used to present the results for both the pine cone jam and pine cone gummy candies.

RESULTS AND DISCUSSION

Sensory evaluations were conducted for all three groups of pine cone confectionery. The linear scale is a widely accepted method for assessing the intensity of sensory evaluation (Gomide et al., 2021). In the case of pine cone syrups (see Fig. 5), a 12 cm intensity scale was used. Participants were asked to rate the intensity of various attributes, including syrup color, aroma, sweetness, pine flavor, and aftertaste.

Color intensity and pine aroma were higher in PSW than in PSB, a significant difference was observed for color intensity ($p \leq 0.04$) and pine aroma ($p \leq 0.02$). It was observed that the color intensity of the syrups was influenced by the type of sugar. White sugar gives the syrup an amber-brown color, providing a milder and sweeter aroma compared to other sugar types (Vicentini-Polette et al., 2019). The added sugar affects not only the color itself, but can also affect the sensory properties of pine cone syrup. White sugar itself does not have a specific aroma, during processing, it is purified, thus acquiring a white color (Zayapor et al., 2021). Therefore, when making syrup from white sugar, the aroma of the product is formed from the added raw material – in this case, pine cones. In contrast, brown sugar gets its characteristic aroma from molasses, which gives it a more aromatic, milder and slightly caramelized taste and aroma (Başar & Boz, 2023).

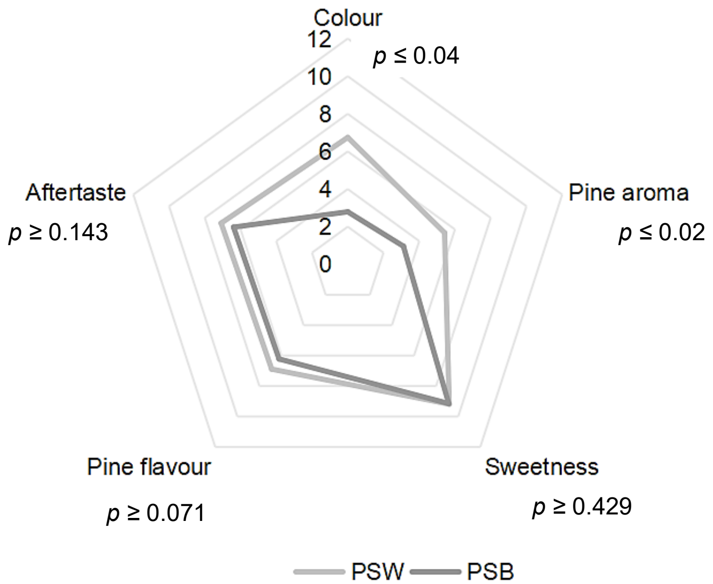

Figure 5. Intensity of pine cone syrups. Pine cone syrup with white sugar (PSW), pine cone syrup with brown sugar (PSB). A significant differences between samples ($p \leq 0.05$) are represented in Fig. 5.

The intensity of the aroma in syrups, as well as the intensity of the color, is determined not only by the added sugar, but also by the pine cones themselves. According to (Karklina & Ozola 2023a), the dominant volatile compound in pine cone syrups made with both white (PSW) and brown sugar (PSB) is 3-carene, which contributes to the resinous and lemony aroma. The concentration of 3-carene is higher and more intense in syrups made with white sugar compared to syrups made with brown sugar. For comparison, it was also observed in this study that PSW had a higher pine aroma than PSB. The molasses in brown sugar suppresses the pine/resin aroma, thus making PSW syrup more intense, as it does not contain molasses. The choice of sugar affects not only the color, aroma and taste of the syrups, but also the sweetness. The sweetness of both pine cone syrups was similar, with no significant difference in sweetness observed between the pine cone syrups ($p \geq 0.429$). Despite the differences in the sugars used and their properties, the amount of sugar added was the same and their sweetness results were similar. In general, white sugar contains pure sucrose, making it much sweeter, which is why it is commonly used in various food products (Arvisenet et al., 2019). Brown sugar, on the other hand, contains molasses, resulting in a lower sweetness intensity compared to white sugar. The presence of molasses affects not only the aroma and taste, but also the overall sweetness of the syrup. The molasses in cane sugar not only provides a pleasant, mild caramelized note, but also imparts a deeper and smoother flavor (Zhao et al., 2024). A slightly higher rating for PSW syrup was observed in terms of taste and aftertaste than PSB, no significant difference in terms of pine flavor was observed for pine cone syrups ($p \geq 0.077$), as well as in terms of aftertaste ($p \geq 0.143$). In general, the choice of sugar affects all sensory properties of the product. Regarding pine cone syrups, consumer comments were taken into account. Consumers, regardless of intensity, prefer PSB in terms of color and taste, as well as aftertaste. 15 out of 23 preferred PSB syrup, because the dark color of the syrup is associated with the color of pine cones. However, 7 out of 23 consumers associate the dark colors of the product with something strong and unpleasant. 8 out of 23 consumers liked PSW better precisely because of its golden color, which they also associate more with pine trees themselves.

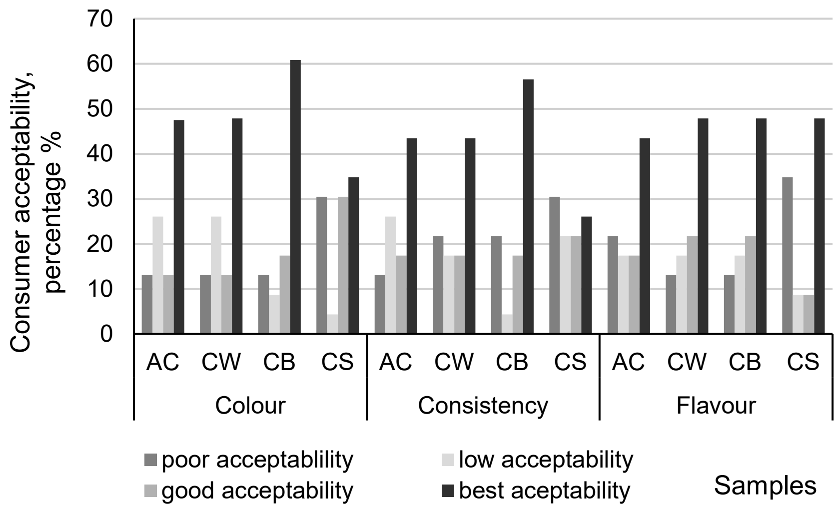

Figure 6. Consumer acceptance of pine cone jams. Apple - pine cone jam without added sugar (AC), pine cone jam with white sugar (CW), pine cone jam with brown sugar (CB), and pine cone jam with stevia (CS).

The arrangement test is used to arrange product samples according to acceptability or liking of the product. The ordering test is usually divided into two types, either the products are arrange from 1 to 4, with 1 being the worst acceptability and 4 being the best acceptability, or vice versa (Yadav et al., 2024). For pine cone jams (Fig. 6), an arrangement test was used in which consumers were required to arrange pine cone jams from 1 with the worst acceptability to 4 with the best acceptability in terms of color, consistency, and taste. When analyzing the arrangement test for pine cone jam, the results obtained indicated that CB 60.86% showed the most favorable results in terms of color. Both jams AC 43.47% and CW 47.82% provided comparable results, while jam

CS 34.78% showed the least desirable color quality. When evaluating the consistency of the jams, CB 56.52% again showed the best acceptability, while AC 43.47% and CW 43.47% of jams showed similar consistency. Conversely, CS 26.08% again received the lowest rating in this category. The taste evaluations did not revealed significant differences between the jams. Pine cone jams CW 47.82%, CB 47.82% and CS 47.82% had the highest taste ratings, which were relatively equal, while jam AC 43.47% received a slightly lower score in this regard. In addition, consumer feedback was systematically analyzed. Overall, participants appreciated the presence of small pine cone pieces in all jams, which contributed to an enhanced taste experience. When comparing jams containing sugar (white and brown sugar), jam CB was noted as having the most positive reviews. However, when it came to jams without added sugar, the most appreciated jam was AC.

Reducing the sugar content in jams affects not only the physical properties (Kārklina & Ozola, 2023b), but also the sensory properties. According to (Gakuru et al., 2019), using sweeter fruits in jam preparation allows for a reduction in the amount of added sugar while maintaining a pleasant sweetness. However, when working with more acidic or sour fruits, it is difficult to add a large amount of sugar to mask their intense taste. However, compared to this study, more sugar is not needed to make the jam more palatable by using more acidic, more intense ingredients, such as pine cones. As consumer comments show, it is possible to make palatable jams without using a large amount of sugar, as was observed with CS and AC jams. In a study conducted by Salgado et al., 2022), different types of added sugars were analyzed, including coconut sugar, brown sugar, white sugar and icing sugar. The results showed that jams made with coconut and brown sugar were darker and more intense in taste, so consumers preferred jams made with white sugar and icing sugar. In this study, participants preferred pine cone jam made with brown sugar to jams made with white sugar or other types. According to a consumer association analysis of consumer comments, brown sugar, the darker color symbolizes pine cones and pine trees more. In addition, a study (Haroon et al., 2024) investigated the sensory parameters of jams with low-calorie sweeteners. The authors tested jams sweetened with stevia, sorbitol, a mixture of stevia and sorbitol, and a control jam made with regular sugar. Overall, sensory attributes were more favorable for jams with added sugar compared to those made with sweeteners. In comparison, this study also observed that pine cone jam with brown sugar had the highest acceptability than jam with stevia.

The Just About Right (JAR) method is widely used in food development to assess consumer preferences and determine optimal feature intensities (Li et al., 2014). When evaluating pine cone candies, the JAR method analyzed several attributes, including appearance, texture, flavor, and aftertaste. Fig. 7, A shows the visual appearance results of the gummy candies. The highest acceptability after the JAR test was observed for pine cone candies CpHM with 78.26%, while pine cone candies CpLM and CA received the lowest scores (26.09). When evaluating consumer comments, they liked the way the cone pieces looked in the candies, but did not like the small nuances in the color, which could be improved by adding more spruce sap in the case of CA candies. Fig. 7, B shows the JAR for consumer acceptance of pine aroma, revealing that pine cone candy CG received the most favorable response with 39.13%, followed by CpHM with 30.43%.

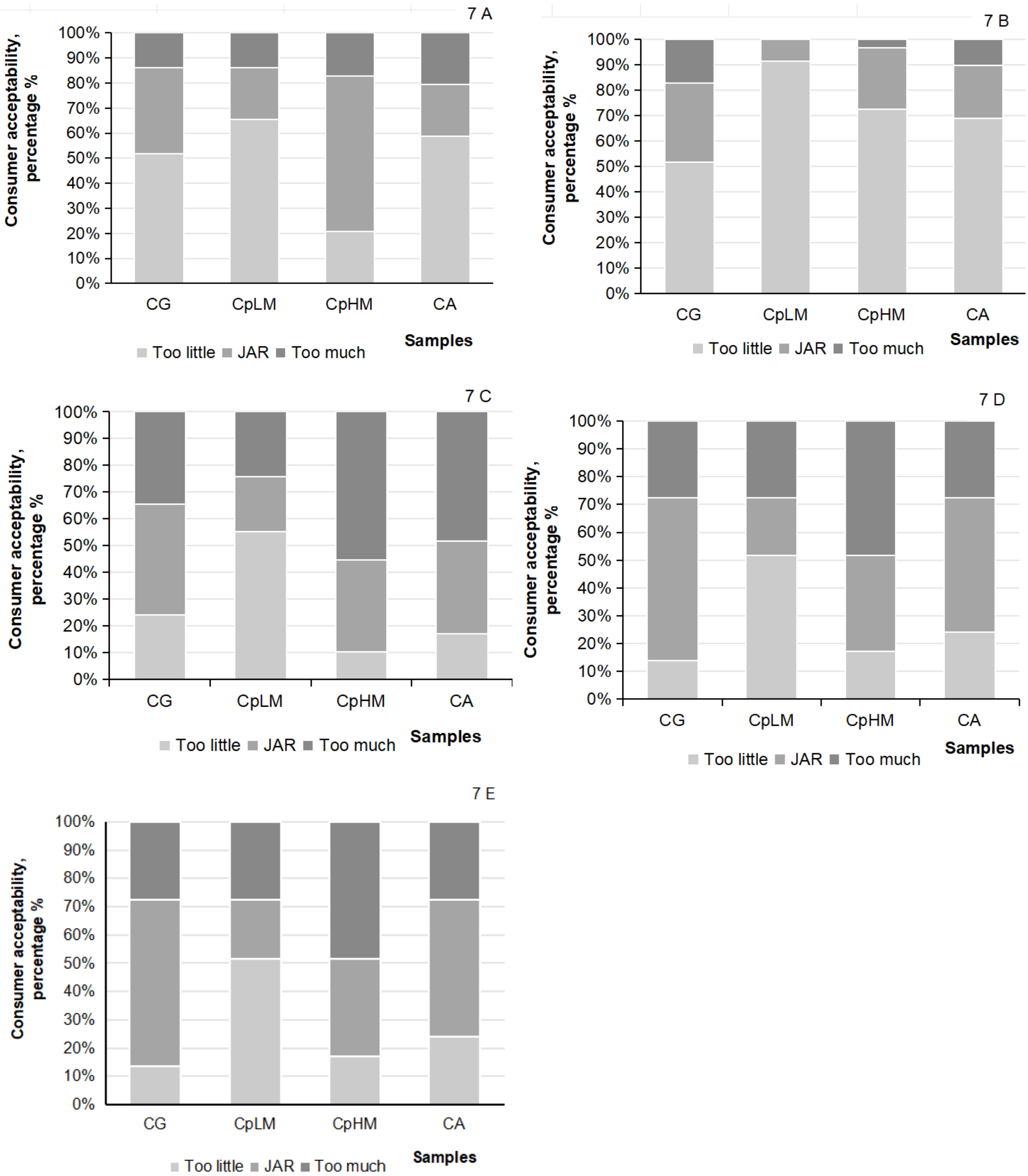

Figure 7. Consumer acceptability of a product features in pine cone candy by Just About Right (JAR) test. Pine cone gummy candy with gelatine (CG), pine cone gummy candy with citrus HM pectin (CpHM), pine cone gummy candy with LM pectin with calcium salts (CpLM), pine cone gummy candy with agar (CA). Appearance of pine cone gummy candies (7, A), aroma of pine cone gummy candies (7, B), structure of pine cone gummy candies (7, C), flavour of pine cone gummy candies (7, D), after-taste of pine cone gummy candies (7, E).

Pine cone candy CpLM received the least favorable rating with 8.60%. The aroma of gummy candy can be influenced not only by pine cones, but also by the thickener used (Pizzoni et al., 2015). Pizzoni et al. (2015), in their study compared the differences in aroma depending on the thickener used using GC-MS (gas chromatography-mass spectrometer) and e-nose (electronic nose). It was concluded that the main reason why thickeners can affect the aroma and flavor of gummy candies is that each thickener has a different effect on flavor release due to its structure and chemical properties, and this effect is further influenced by the candy manufacturing technology, which is also different for each thickener. The aroma and flavour in gummy candies can also be influenced by other added ingredients, such as added pine cone syrup or spruce sprout juice, which in both cases give a resinous flavor, but in varying intensities. In comparison, the predominant volatile compound in pine cone syrup is 3-carene (22.6%), which gives a resinous and lemony aroma. The second compound longifolene (17.0%), which gives a sweet and coconut aroma, and limonene (13.8%) which gives citrus aroma (Karklina & Ozola, 2023a). But in spruce sprout juice, the dominant compound is limonene (37.76%), the second compound is bornyl acetate (21.6%) which gives a pine / resin aroma, while 3-carene is only the 5th most abundant compound at 6.92% (Karklina, 2024).

From this it can be concluded that consumers liked the CG candy with added spruce sprout juice better, because it gives a milder and more pleasant resin aroma and taste than those without spruce sprout juice, although the CpHM candy did not have spruce juice added, so its results seemed good. This could be influenced by the results discussed above when evaluating pine cone syrups. Fig. 7, C shows the JAR for consumer acceptability of texture, CG pine cone candy was again in first place with a JAR score of 52.17%, while both CpHM and CA combined score 43.48%. In a USA study (Ataman, 2023), they concluded that consumers prefer gummy candies that are soft like pectin gummy candies. But in this study, the opposite was observed, with gelatin gummy candies receiving higher votes for the best acceptability than pectin gummy candies. Gummy candies with agar - agar does not require a lot of sugar as it is with pectin and are much more suitable for vegans therefore, its popularity might be greater for use in jelly candies (Tarahi et al., 2023). But the consumers commented that CA texture resembles cartilage rather than candy, so the liking score was not as high as CG candy. However, in terms of taste and aftertaste, CA was rated well. Fig. 7, D shows the JAR for consumer acceptability of the taste, where pine cone gummy candy CG achieved the highest acceptability of 73.91%, while a slight decrease was observed for pine cone gummy candy CA at 60.87%. The lowest ratings for the taste of pine cone gummy candy were observed for CpLM and CpHM, 26.09% and 43.48%, respectively. The difference in taste could be based on the previously discussed aroma that forms the candy. Because aroma and taste are in a sense closely related as in flavour. Pine cone syrup was added to CpLM and CpHM, which was intense in terms of taste, as well as volatile compounds that shape the aroma can influence consumer choices. Finally, Fig. 7, E shows the JAR for consumer acceptability in the aftertaste, which reflects the taste results. Overall, the most significant consumer acceptability was observed for the CpHM and CG variants of pine cone gummy candies. Based on consumer comments, these candies had a more pleasant taste. According to (Vojvodić Cebin et al., 2024) the gelatin and sugar mixture provides a highly rated sensory evaluation of sweetness and chewiness, which was also observed in this study for taste, aftertaste. Pectin in candies requires both sugar and an acidic environment to create a gel-like structure (Gawkowska et al., 2018). In this study, the sugar content was provided by adding pine cone syrup prepared with brown sugar, while the acidic environment was provided by added citric acid, as well as the pine cones themselves. According to (Karklina & Ozola, 2023a), the total soluble solids in pine cone syrups with brown sugar added can range from 61.3 ± 0.83 to 64.3 ± 0.26 °Bx, while the pH is 3.44 ± 0.01 to 3.66 ± 0.02, which is necessary for pectin to function. According to (SOSA Pectin) the manufacturer of HM and LM pectin, the necessary conditions for pectin to work are a pH value of 2.8 to 4.7 and a soluble solids content of at least 60 Bx° and 80 Bx°. In particular, the inclusion of pine cone pieces was generally considered acceptable by respondents, indicating a positive perception of this ingredient in gummy candy formulations. Sweets are considered one of the most popular confectionery products with low nutritional value but high calorie content. Adding more nutritious ingredients or ingredients with higher bioactive compounds could increase the value of gummy candy (Vojvodić Cebin et al., 2024). Adding pine cones to gummy candy can increase the value of gummy candy (Ferreira-Santos et al., 2020).

CONCLUSIONS

Sensory assessment and consumer preferences in general showed a confirming trend towards healthier choices and options for new product development incorporating less traditional ingredients, such as pine cones.

From the assessed pine cone syrups in terms of color, taste and aftertaste consumers preferred sample PBS (pine cone syrup with brown sugar) instead of PSW (pine cone syrup with white sugar) due to a lack of sensory parameter intensity.

For jams, CB (pine cone jam with brown sugar) also showed better results in terms of color and consistency, but in terms of taste, CW (pine cone jam with white sugar), CB and CS (pine cone jam with stevia) showed equally good results.

The evaluated pine cone gummy candies where various product properties where evaluated using JAR test, concluded that pine cone gummy candy with gelatin showed the best results in terms of aroma, structure, taste and aftertaste, but in terms of appearance, the highest results were detected in sample CpHM (pine cone gummy candy with HM pectin).

In conclusion, it is possible to develop confectionery products that incorporate pine cones, and the industry can innovate in ways that meet consumer desires for delicious sweets while addressing current health concerns (reducing sugar). This approach not only satisfies the growing demand for healthier options, but also promotes sustainable sourcing practices, which ultimately benefits both producers and consumers.

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Effect of zeolite, clay and peat on salt stress tolerance of lettuce (*Lactuca sativa* L.)

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Abstract. The present study aimed to investigate the effects of natural zeolite, clay and peat amendments on the growth and NaCl absorptions of lettuce (*Lactuca sativa* L.) under gradually increasing salinity. Four different growing media based on quartz sands with 10% additions of zeolite, clay and peat were tested. The worst effect of NaCl on plant biomass was evident at the highest salinity levels for zeolite applications. While adverse salinity impact on leaf and root biomass was least pronounced in treatments with peat additives. As expected, the lowest Na concentrations in plant tissues were found in the growing media supplemented with zeolite. In the case of Cl, however, it was the opposite - lettuce leaves accumulated significantly higher chloride concentrations in the zeolite variants in salinity treatments above 20 mM NaCl. In the control, clay and peat treatments, as the substrate salinity increased, the Cl level in the plant increased similarly. Adverse changes in leaf chlorophyll concentration (SPAD) and photosynthetic rate (µmol m^{-2} s^{-1}) parameter appeared under salinity concentrations above 20 mM and were more pronounced in zeolite and sand substrate. According to the obtained results, peat additives can effectively mitigate the harmful effects of excessive salts by binding and immobilizing them as well as improving the water-holding capacity and nutrient availability. The study also concluded that natural zeolite successfully immobilizes cationic sodium, but the harmful effect of chlorine significantly reduced plant growth and photosynthetic performance. Clay additives to the growth medium showed the potential to reduce the adverse effects of salinity on lettuce, however, under the experimental conditions implemented, the effect was small.

Key words: sodium chloride, pot experiment, organic matter, plant biomass, photosynthesis.

INTRODUCTION

Elevated salinity of soil and irrigation water is a major and increasing problem for agricultural production in the world, especially in the arid and semi- arid regions where lives more than 75% of the world's population (Singh, 2015). It is estimated that up to 20% of arable and 50% of the irrigated land worldwide is salt-affected (Ruan et al., 2010) with estimated economic impacts as high as \$300 ha^{-1} resulting in the annual loss of 27.3 billion USD in global income (Munns & Gilliham, 2015; Elmeknassi et al., 2024). In general, the soil is considered to be saline and inhibits water uptake by plants if the electric conductivity - EC (available salts in the soil pore water) is over 400 mS m^{-1}

(equal to ~ 40 mM NaCl). While various salt compounds are present in the soil solution, sodium chloride is the most predominant one (Evelin et al., 2019). It is well known that soil salinization adversely affects the environment, agroecosystems, agricultural productivity, plant yield quality and sustainability. Many investigations have demonstrated the harmful effect of salinity on plants. Thus, cellular water deficit, inhibited membrane functions, ion toxicity, nutrient deficiencies, decreased chlorophyll concentration and the activity of several enzymes and oxidative stress can lead to disturbance of various metabolic processes and growth inhibition, molecular damage, and even plant death (Balasubramaniam et al., 2023). Additionally, osmotic stress from elevated salinity harms the germination of many plant species (Atta et al., 2023). High salt concentrations decline soil porosity and structure, soil aeration and water conductance. In addition, elevated Na^+ ion concentrations interfere with K, Ca and Mg decreasing the availability of these ions to plant uptake, as well as adversely affect the availability of Fe, Mn, Zn and Cu. The degree of salt tolerance greatly varies among plant species and varieties, also at different developmental stages (Munns & Tester, 2008).

Lettuce (*Lactuca sativa* L.), belonging to the *Asteraceae* family, is one of the main leafy vegetables produced and consumed in the world (Medina-Lozano et al., 2021). In general, lettuce is considered as a moderate salt-tolerant crop (Fernández et al., 2016) or even sensitive according to other authors (Shannon & Grieve, 1999; Xu & Mou, 2015). Previous researches show that salinity levels, in terms of EC, above 2.7 dS m^{-1} reduce lettuce growth and yield (De Pascale & Barbieri, 1995). The salinity threshold value for lettuce in different research was determined between 1.1 and 1.3 dS m^{-1} and the relative yield decrease after reaching this threshold was 9.3% to 13% (Shannon & Grieve, 1999; Ünlükara et al., 2008). However, the results of a field trial in Israel demonstrated that the yield and quality of iceberg lettuce were not significantly affected at 4.4 dS m^{-1} irrigation water salinity (Pasternak et al., 1986). Although it is difficult to determine why there are such differences in the reported results other authors point out that the experiment in Israel did not include a sufficient number of experimental treatments as well as soil in the experiment was gypsiferous and salinity effects can be partially offset by over-irrigation (Russo, 1987; Shannon & Grieve, 1999). However, there is clear evidence that indicates large differences in salt tolerance among different varieties of lettuce.

The results of studies with zeolite confirm it as a suitable material for the reduction of salinity. As reported, 15% addition of zeolite reduced salinity impact on plants by 42% (Koushafar et al., 2011). As zeolites are characterized by a high water and cation exchange ability it makes them potentially useful in the field of crop production on saline soils (Cataldo et al., 2021). On the other hand, the addition of natural zeolite can cause excessive adsorption and lead to the immobilization of essential plant nutrients with an adverse effect on plant growth. Abdelrazek (2018) reported that the addition of peat moss to saline calcareous soil improved tomato growth indices. Several other studies report that the high content of organic matter and tremendous adsorptive interfaces confirm peat as a very effective sorbent for the immobilization or removal of heavy metals and NaCl (Pelinsom Marques et al., 2020; Ondrasek et al., 2021). As an incorporation of clay into growing media positively influences the water retention characteristics of the soil (Jean-Charles, 2009) such a phenomenon could mitigate the salinity effects on plants. Additions of zeolite, peat, or clay have the potential to reduce the adverse effects of salinity on plant growth (Table 1) although their use can be limited by material cost and availability.

Table 1. The role of natural zeolite, peat and clay as soil amendments for mitigating the negative impacts of soil salinity (Jean-Charles, 2009; Pelinsom Marques et al., 2020; Cataldo et al., 2021)

	Ion exchange capacity		Absorption of toxic ions	Improving soil structure	Water retention	pH stabilization	Enhanced nutrient availability
	cations	anions					
Natural zeolite	×		×	×	×	×	×
Peat	×		×	×	×	×	×
Clay	×		×				

With the massive increase of intensive agriculture farming systems today, vegetable crop cultivation requires a high input of fertilizers and irrigation water, which can eventually lead to the elevation of soil salinity. Therefore, the importance of research on different management practices aimed at the prevention of soil and water salinization and mitigation of salinity effects on plant growth is critical.

The objective of our research was to determine the effects of salinity on lettuce growth and how management practices - addition of zeolite, clay and peat to soil media can mitigate the adverse effects of salinity on the growth and photosynthetic (SPAD, photosynthetic rate, stomatal conductance) parameters of lettuce.

MATERIALS AND METHODS

Lettuce (*Latuca sativa* L., variety 'Grand Rapids') was used as model culture. Commercial lettuce seeds were sown into 1L round polyethylene pots containing quartz sands and a mixture of quartz sands (Ltd. Saulkalne S, Saulkalne, Latvia) with 10% of studied amendments (zeolite (3–5 mm), clay and peat moss). Three pots for each treatment and three plants per pot under controlled growth conditions (photoperiod 16 h, photon flux density 250 $\mu mol\ m^{-2}\ s^{-1}$ supplied by fluorescent tubes, day/night temperature 20/18 °C, relative air humidity 60–65%) were used. Individual pots were randomly located (Table 2). Substrate water content was maintained at not less than 60% of full water-holding capacity. Moisture level throughout the experiment was maintained by weighing each pot and adding deionized water. Optimal concentrations of all macro and micronutrients (mg L^{-1}): 120 N, 60 P, 150 K, 800 Ca, 50 Mg, 50 S, 30 Fe, 0.5 Cu, 1.5 Mn, 0.02 Mo, 0.2 B in the substrate were provided in each pot at the beginning of the experiment. The impact of salinity on plant growth indices was studied at four levels of salinity - 0, 10, 20, 30, 40 mM NaCl. Salt stress was imposed by gradually adding NaCl to irrigation water over 7 days until the final concentration was reached.

Table 2. Randomized complete block design used in experimental pot layout (three plants per pot)

P10	C30	S0	S10	S0	Z20	S20	Z0	P40	Z10
S40	S30	S30	Z40	Z10	P20	S40	P30	Z0	P0
Z20	C40	Z30	P20	Z30	C0	C0	S10	P10	C40
P40	C0	P0	C20	Z40	P0	C10	P30	C30	C20
S30	C10	S10	S20	S20	P10	Z20	C10	S0	S40
Z10	C30	Z30	Z40	P40	P20	C40	C20	P30	Z0

S – sand; Z – zeolite; P – peat; C – clay. 0, 10, 20, 30, 40 – salinity levels (mM NaCl).

The experiment was terminated and measurements were made 30 days after the start when visual signs of damage to plants were detected. A portable chlorophyll meter SPAD 502 (Minolta, Warrington, UK) was used for non-destructive chlorophyll determination. Photosynthetic characteristics: photosynthetic rate (A, $\mu mol\ m^{-2}\ s^{-1}$), stomatal conductance (gS, $mol\ m^{-2}\ s^{-1}$), were measured with ADC portable LCi Ultra Compact Photosynthesis system (ADC BioScientific Ltd., UK) on a fully developed young leaf. The fresh mass of plant leaves and roots was estimated immediately after harvesting, and the dry mass was determined after drying (+60 °C for 24 h).

The dry plant samples were dry mineralized with HNO_3 vapor and re-dissolved in HCl (3:100). The level of Na was estimated by microwave plasma atomic emission spectrometry (4200 MP-AES, Agilent, Santa Clara, CA, USA) according to manufacturer's instructions and Cl content was determined by $AgNO_3$ titration (Osvalde, 2011).

The statistical analysis of the results was carried out using MS Excel 2016 software. Standard errors (SE) were calculated to reflect the mean results of analyzed parameters. T-test 'Two-Sample Assuming Equal Variances' at $p < 0.05$ was used for testing the effect of different amendments on plant growth under salinity stress.

RESULTS AND DISCUSSION

Impact of NaCl on Na^+ and Cl^- accumulation in plant tissues

In general, Na and Cl ion concentrations drastically increased in the leaves of lettuce cultivated in the presence of increasing substrate salinity (Fig. 1). While tissue Na and Cl concentrations increased with increasing substrate salinity, the character of the response was significantly affected by the additives used.

The most pronounced increase in leaf Na concentration at a moderate to high external salinity level was detected for quartz sand substrate with the maximum concentration - 1.803% Na^+. The lowest Na concentrations in lettuce at all salinity levels were found for zeolite reaching 0.931% Na^+. Conversely, while Cl^- levels under rising salinity in treatments with sand, peat and clay increased similarly, in a case with zeolite lettuce leaves accumulated significantly higher concentrations in salinity treatments above 20 mM NaCl. Such a phenomenon can be explained by the natural zeolite's negatively charged framework with ability to effectively attract cations. Natural zeolites can also be suitable for binding anionic contaminants, such as chlorine ions, but only after surface modification by reversing their surface charge using appropriate charge-altering compounds (Senila & Cadar, 2024). Thus, our study clearly shows that natural zeolite are not an effective remedy for anion absorption due to its negative charge. However, it is undeniably a suitable material for reducing the impact of Na pollution on plants. In general, organic matter (peat) and clay have several properties with the potential to improve the structure of the soil and plant growth in saline environments, including improvement of the soil cation exchange capacity (CEC), which helps bind potentially harmful sodium ions. Our study demonstrated the significant effect of peat and clay additives on the uptake of Na in lettuce leaves when NaCl concentration in the substrate exceeds 30 mM. Although, peat amendments can serve as a sorbent for anion contaminants which is primarily attributed to its rich content of humic substances and various functional groups (carboxyl and phenolic) (Yuliani et al., 2022). As well, several studies have indicated that the presence of clays in soil enhances the sorption of anionic pollutants, but such properties are dependent on clay type and its specific physicochemical properties (Wu et al., 2022). However, our findings demonstrate insignificant peat and clay effects on chlorine ion uptake by lettuce plants (Fig. 1, B).

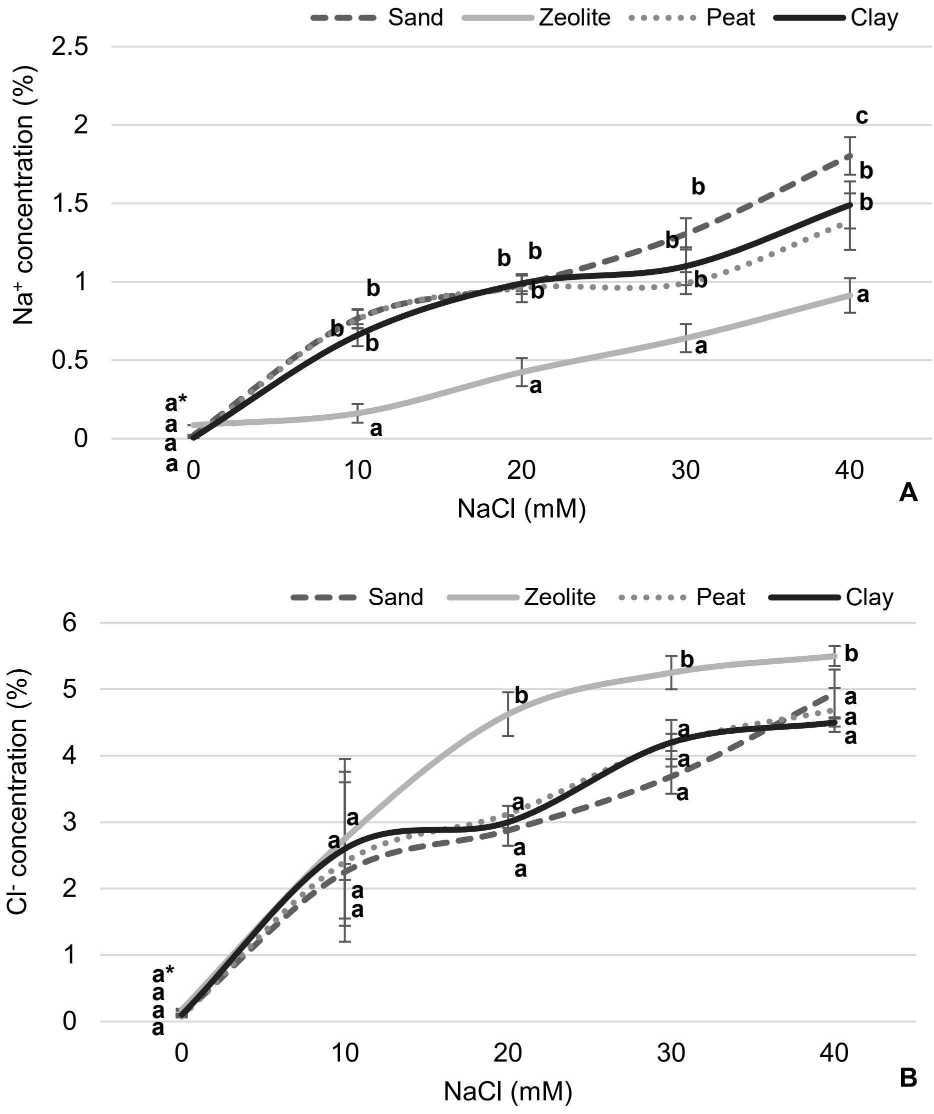

Figure 1. Accumulation of Na^{+} (A) and Cl^{-} (B) in leaves of Latuca sativa dependent on different substrate additives (sand, zeolite, peat and clay) under increasing salinity.
*Means with different letters for each NaCl treatment level were significantly different (t-Test, $p < 0.05$).

Impact of NaCl on plant fresh and dry mass of leaves and roots

It is widely documented that elevated soil salinity affects almost all aspects of plant growth and development, including vegetative growth, photosynthesis, reproductive development and germination (Chinnusamy et al., 2006). As established in other research, lettuce is considered as relatively sensitive to elevated soil salinity, which considerably reduces its growth parameters, including root and shoots fresh and dry weight (Cheruth et al., 2016; Adhikari et al., 2019; Zhang et al., 2021). Also in our experiment reduction in fresh and dry weight of lettuce shoots and roots was observed under increasing NaCl concentrations in all substrates (Fig. 2; Fig. 3).

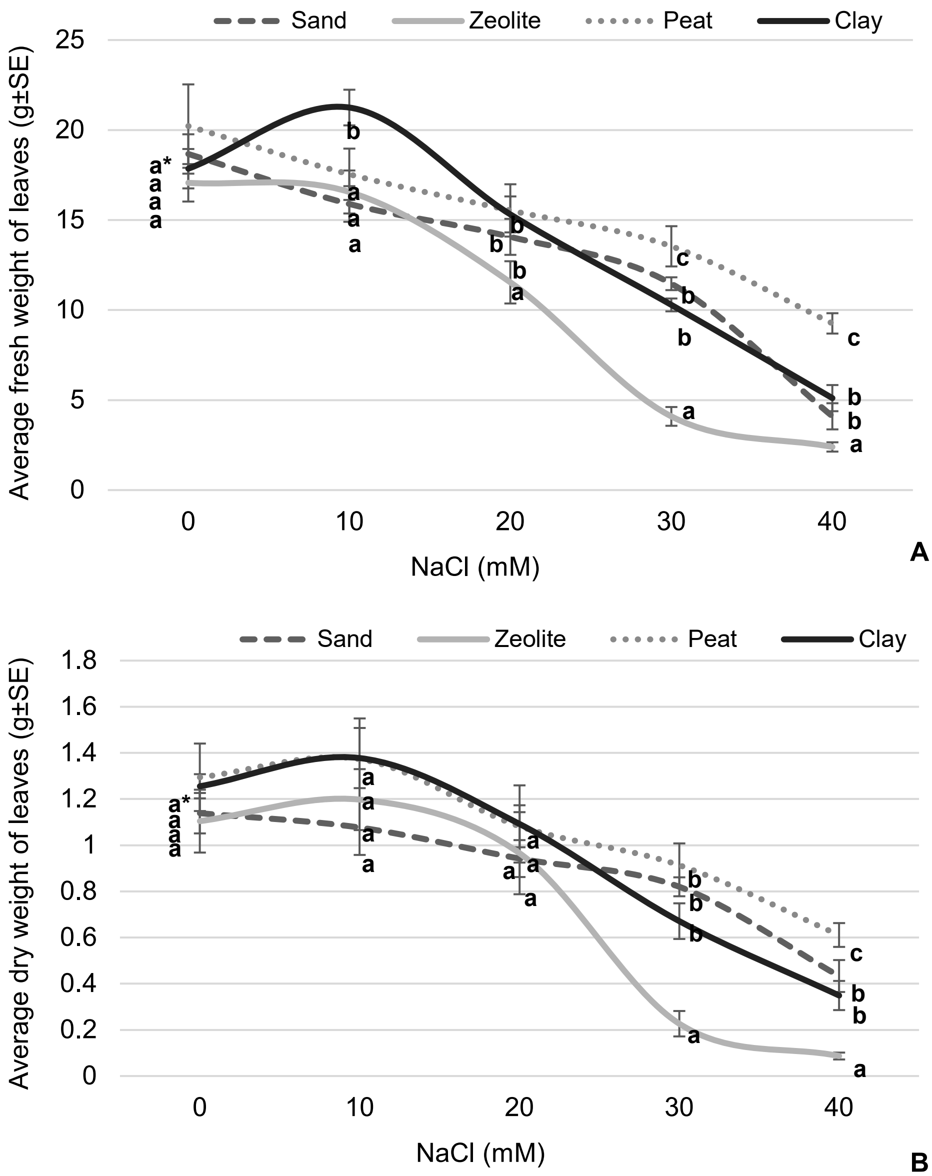

Figure 2. The effects of elevated salt (NaCl) levels on fresh (A) and dry (B) leaf mass of lettuce cultivated in substrates with different amendments.

*Means with different letters for each NaCl treatment level were significantly different (*t*-Test, $p < 0.05$).

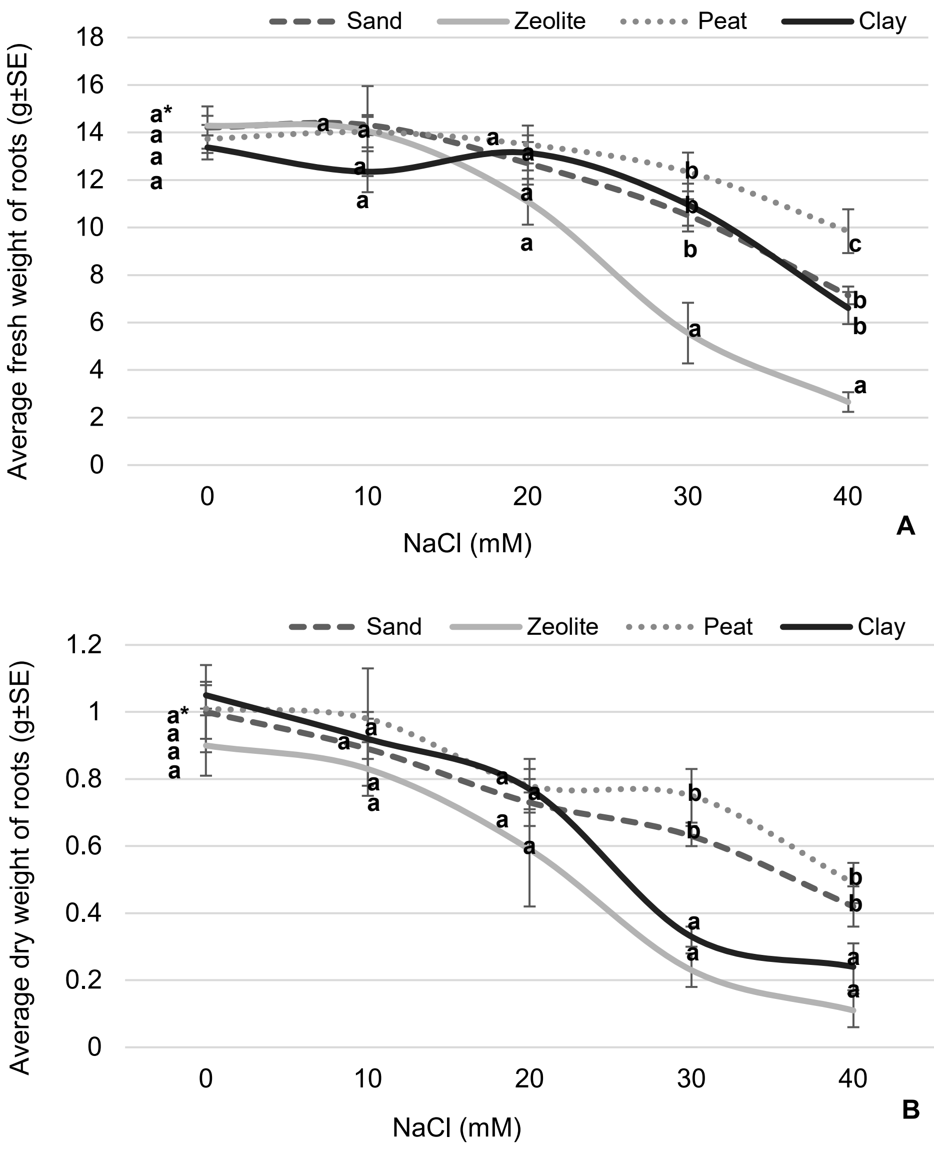

Figure 3. The effects of elevated salt (NaCl) levels on fresh (A) and dry (B) root mass of lettuce cultivated in substrates with different amendments.

*Means with different letters for each NaCl treatment level were significantly different (*t*-Test, $p < 0.05$).

While in control (0 mM NaCl) plant shoot and root fresh weight was without significant differences among different substrates, gradual reduction of studied parameters was observable above 20 mM of salinity. The highest shoot fresh and dry weight (9.26 ± 0.56 g and 0.72 ± 0.08 g) under 40 mM salinity was found in the substrate with peat additive. While the lowest fresh weight of shoots and roots was recorded in a substrate with zeolite. Moreover, measured parameters were even lower than those obtained in quartz sands. Such results are consistent with a study made by Babaousmail et al. (2022) where zeolite treatment positively influenced the fresh weight of lettuce only at low salinity concentrations. On the other hand, there are several studies where natural zeolite application mitigated the adverse effects of salinity stress on other plant species: barley (*Hordeum vulgare*) (Al-Busaidi et al., 2008), canola (Brassica napus) (Bybordi, 2016) and ryegrass (*Lolium perenne*) (Rahimi et al., 2021). It should be noted that experiments with barley and canola were conducted in open field conditions where harmful Cl ions as anions may be exposed to additional leaching. While studies with ryegrass were carried out as pot experiment in a greenhouse, chlorine concentrations were not measured in substrate or plant material. Apparently harmful effect of higher levels of chlorine in zeolite-containing substrate depressed its positive effects on sodium ion binding capabilities. As reported in other studies Cl^- ion is more toxic to plants than Na^+ (Li et al., 2017). The vast majority of the research dedicated to salinity issues has been carried out in the presence of NaCl salt, but very scarce information is available using individual salts containing Na^+ or Cl^-.

The addition of peat (organic matter) is considered as effective method in reducing the damage of salinity to plants. Organic matter improves water holding capacity, soil aeration and promotes the secretions of organic acids from roots that regulate soil pH and reduce the adverse impact of salinity. Besides, additional organic matter decomposed by soil microorganisms remarkably contributes to nutrient availability in the soil (Ondrasek et al., 2021). Our study confirms the beneficial effect of peat on plant growth parameters under increasing salinity, especially in salinity levels above 30 mM.

In general, the salinity effect on lettuce root fresh and dry weight had a similar pattern as in the case with leaves (Fig. 3). However, there was one exception. Although clay additives in the substrate under saline conditions gave similar trends in terms of leaf and root fresh weight, root dry weight was even lower than that obtained in the stand-alone quartz sand substrate.

Table 3. Effect of salinity on dry and fresh weight ratio of lettuce leaves (DW/FW)

	0 mM	10 mM	20 mM	30 mM	40 mM
Sand	0.061±0.006**a***	0.068±0.003**a**	0.067±0.004**a**	0.072±0.002**a**	0.106±0.007**b**
Zeolite	0.065±0.003**a**	0.072±0.007**a**	0.084±0.006**a**	0.089±0.004**b**	0.14±0.009**b**
Peat	0.064±0.007**a**	0.078±0.008**a**	0.07±0.004**a**	0.067±0.009**a**	0.078±0.010**a**
Clay	0.07±0.004**a**	0.065±0.009**a**	0.071±0.009**a**	0.078±0.003**a**	0.105±0.008**b**

*Means with different letters in a row were significantly different from control (0 mM NaCl) (*t*-Test, $p < 0.05$).

As reported before in experiments with lettuce, fresh weight of plant leaves was more sensitive to salinity than dry weight (Shannon et al., 1983; Pérez-López et al., 2013; Xu & Mou, 2015). Similarly, our results demonstrate a significant reduction in leaf water content under the highest salinity (40 mM) in treatments with all substrate additives except peat (Table 3). Such results underline the organic matter's positive effect on soil moisture retention and improved water availability to plants under salinity stress. Our results are consistent with the findings of Suvendran et al. (2024) and Mahmoodabadi et al. (2011) where in experiments with pea and soybean organic matter additions significantly improved plant dry weight under salinity stress.

Effect of NaCl on plant photosynthetic parameters

It is well-documented that abiotic stress caused by elevated soil salinity adversely affects the photosynthesis process in non-halophytic plants (Chaves et al., 2009). The leaf chlorophyll content serves as a key indicator of the plant's photosynthetic capacity. Chlorine ions have been traditionally considered harmful to plant growth. However, Cl^{-} ion levels below the toxicity threshold can be beneficial for higher plant growth under water-sufficient conditions, with physiological functions that upgrade cell water balance (Franco-Navarro et al., 2021). Our experiment also demonstrated a slight improvement in chlorophyll concentration at 10 mM salinity in all substrates where additives were used (Fig. 4). Thereby, it can be concluded, that in low salinity, clay, peat and zeolite amendments ensured sufficient water availability. Moreover, in clay and peat-containing substrates a significant decline in chlorophyll content was detected only in the highest salinity treatment. While in pure sand and zeolite-containing substrates a significant decrease in chlorophyll content was found already above 10 mM salinity.

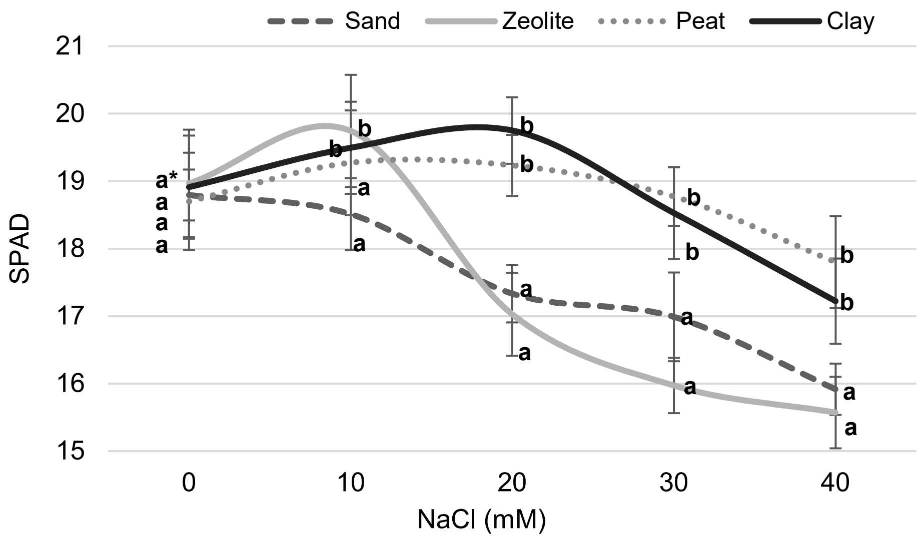

Figure 4. Effect of NaCl on leaf SPAD values of lettuce cultivated in substrates with different amendments.

*Means with different letters for each NaCl treatment level were significantly different (*t*-Test, $p < 0.05$).

Such results support previously determined salinity threshold values (1.1 to 1.3 dS m^{-1}) for lettuce (Shannon & Grieve, 1999; Ünlükara et al., 2008). It can be stressed, that peat and clay amendments significantly improve lettuce chlorophyll content and increase salt stress tolerance.

Our study approved the already-known fact that the chlorophyll content is widely proportional to the rate of photosynthesis (Fig. 5). Harmful effect of salt stress on lettuce photosynthetic rate was evident for all substrates at salinity levels above 20 mM. However, peat and clay amendments ensured significantly higher values for the highest salinity treatments.

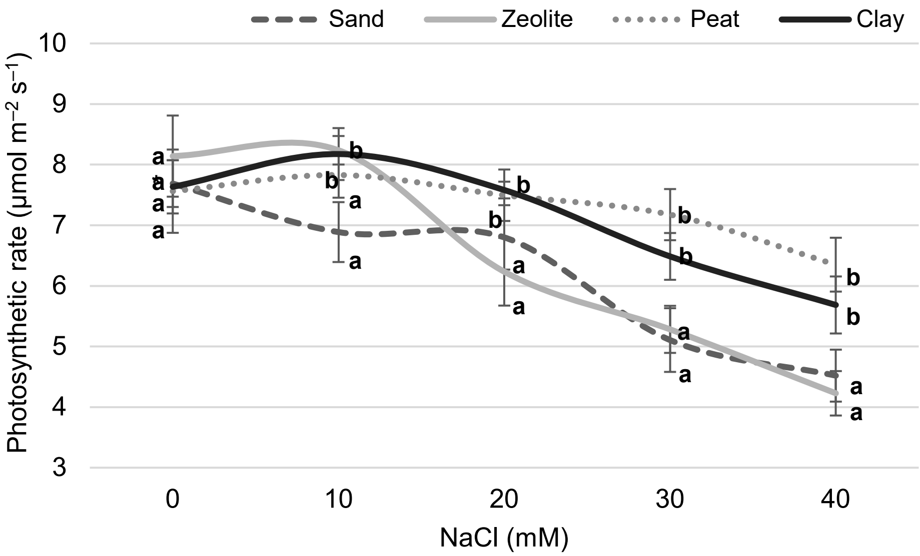

Figure 5. Effect of NaCl on leaf photosynthetic rate (μmol m^{-2} s^{-1}) of lettuce cultivated in substrates with different amendments.

*Means with different letters for each NaCl treatment level were significantly different (*t*-Test, $p < 0.05$).

A similar trend was observed in the case of stomatal conductance measurements. In general, the adverse effect of salinity on plant stomatal conductance was found (Fig. 6).

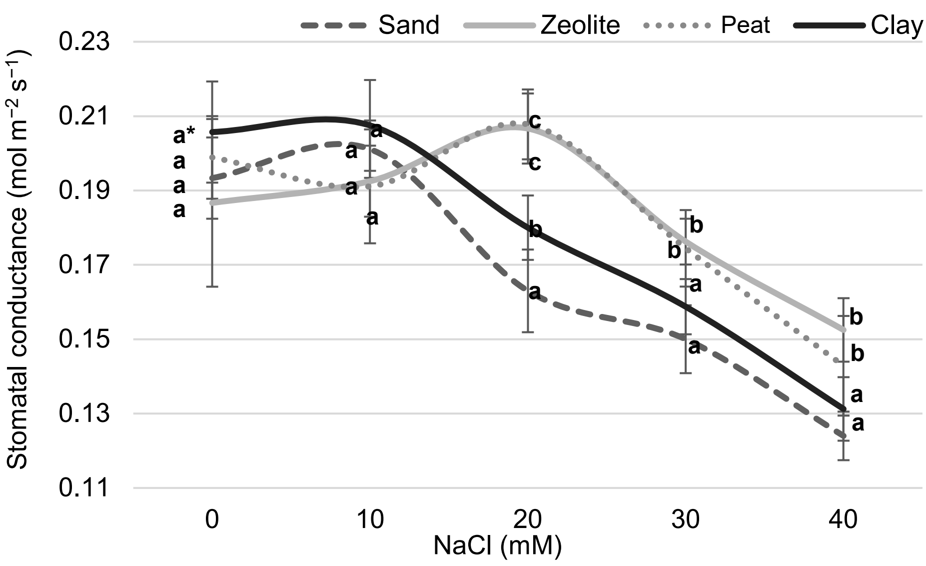

Figure 6. Effect of NaCl on stomatal conductance (mol m^{-2} s^{-1}) of lettuce cultivated in substrates with different amendments.

*Means with different letters for each NaCl treatment level were significantly different (*t*-Test, $p < 0.05$).

Such results indicate, that salt-induced decrease of photosynthetic rate was at least partly caused by stomatal closure. Despite the fact, that salinity levels above 20 mM reduced chlorophyll concentration and photosynthetic rate expressly in substrate with zeolite additions, the stomatal conductance was high and comparable with peat amendments. Such a decline in photosynthetic rate without a corresponding decline of stomatal conductance can be interpreted as a direct effect of Cl^- toxicity on plant photosynthesis, as chlorine levels in a substrate with zeolite were significantly higher (Fig. 1).

CONCLUSION

Lettuce demonstrated high sensitivity to soil salinity, as its growth was strongly reduced by salinity levels above 20 mM. Natural zeolite amendment successfully immobilized cationic sodium and improved water availability, but the harmful effect of enhanced uptake of chlorine significantly reduced plant growth and photosynthetic performance. Our study confirms the beneficial effect of organic matter (peat) on plant growth parameters under increasing salinity, especially in salinity levels above 30 mM. Although clay additives to the growth medium showed the potential to reduce the adverse effects of salinity by promoting lettuce photosynthetic rate and total concentration of chlorophyll the effect on plant biomass gain was small.

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Process of heat treatment and changes in garlic properties

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Abstract. This paper aims to present the results of research focused on the heat treatment of garlic (*Allium sativum*) into black garlic. The research compared three varieties of classic kitchen garlic (Dukat, Topaz and Sabagold), grown in the Czech Republic. The course of heat treatment in a hot air dryer was investigated at 60 °C. Changes in the weight and moisture of the samples were monitored gravimetrically for 78 days. The dry matter content was measured gravimetrically after drying at 105 °C. There were certain differences between the varieties studied. The intensive decrease in water content, dry basis u (g g^{-1}) during the first 20 days was the fastest in the Topaz variety, when it dropped below 0.4 (g g^{-1}) after only 9 days. In the Dukat and Sabagold variety water content, wet basis w (%), from the original values w = 62 to 66% dropped below 30% within 20 days, and in the Topaz variety below 20%. Changes in the colour of garlic cloves were measured by A CM-600d spectrophotometer. During the black garlic processing, its gradual darkening occurred. Lightness L* decreased in the Dukat variety from 80.39 to 27.47, Topaz from 78.29 to 29.09 and Sabagold from 83.64 to 28.72. In all varieties, colour changes occurred. Greenness (-a*) changed from the 9th day to a redness (a*) whose saturation gradually decreased. The yellowness (b*) of all varieties also decreased significantly.

Key words: CIELAB system, colour, garlic, heat treatment, Maillard reaction, moisture, spectrophotometer, temperature.

INTRODUCTION

Garlic (*Allium Sativum*) is a traditional vegetable that is widely used in cooking worldwide (Makarichiana et al., 2021; Qiu et al., 2022; Makarichiana et al., 2024; Park, et al., 2024). In addition to its interesting taste, its medicinal properties are also known (Zhang et al., 2021; Zerlasht, et al., 2024).

Another variant of garlic use, known for many centuries, is the heat treatment of garlic and the preparation of so-called black garlic (Turan & Şimşek 2022; Vathsala et al., 2023). The process of producing black garlic is based on the effect of higher temperature and humidity on garlic for a longer period of time. With this treatment, garlic loses its typical aroma (some people believe it is a smell) and pungent taste, and its colour also changes from light to dark. These changes are caused by the Maillard reaction. The result is not only changes in physical properties, but also significant changes in chemical composition (Navrátilova, 2019; Turan & Şimşek 2022; Vathsala et al., 2023).

Compared to raw garlic, black garlic contains a greater number of substances with antioxidant effects, such as polyphenols, flavonoids and other organic compounds. These substances have proven medicinal effects, such as anti-inflammatory, antimicrobial, antidiabetic, hepatoprotective, neuroprotective, antitumor and others (Navrátilova, 2019; Turan & Şimşek 2022; Vathsala et al., 2023).

Various methods and procedures for processing black garlic at different temperatures have been tested for preparation e.g. (Sailah et al., 2024). The recommended temperature according to research results and analyses (Zhang et al., 2016) is below 70 °C.

Black garlic is prepared in a simpler home form by sealing it in containers and slowly baking it at higher temperatures, usually at 60 °C, for 3 to 4 weeks (Mikšík, 2015).

The aim of this article is to show the course of changes in the basic physical properties of garlic, i.e. moisture and colour, during its processing using the Maillard reaction by preparing black garlic using a traditional home method.

MATERIALS AND METHODS

For this research, fresh garlic was used a few days after harvest, grown in the Czech Republic. Three varieties of garlic were examined: Dukat, Topaz and Sabagold. The laboratory measurements were carried out at the Faculty of Engineering CULS Prague. The process of producing black garlic was based on traditional home preparation. After measuring the colour of the cloves, the fresh garlic bulbs were weighed (net weight), individually wrapped in aluminium foil and placed in measuring cups, the gross weight was weighed and placed in a Memmert laboratory heating and drying oven. The temperature in the oven was automatically maintained at 60 °C, while the ventilation was closed.

The samples were weighed every day during the entire measurement period of 78 days. Samples were weighed during the drying on the digital laboratory balance KERN-440-35N with a maximum load weight of 400 g, with resolution 0.01 g and accuracy ± 10 mg and values were recorded.

After the measurement of the black garlic production process was completed, the temperature in the oven was increased to 105 °C and after drying for 25 days until the weight stabilized, the dry matter of the samples was determined.

After the measurement of the black garlic production process was completed, the temperature in the oven was increased to 105 °C and drying at this temperature took place for 25 days until complete drying, i.e. until the weight stabilized, and thus the dry matter of the samples was determined.

During the production of black garlic, changes occur that are manifested by weight loss, just as during drying. Therefore, it is possible to follow the methodological procedure used in previous publications focused on drying agricultural materials, e.g. (Kic, 2018; Kic, 2019). The main parameters of garlic changes during the processing are calculated from the measured values of garlic samples. Water content, dry basis u is defined as the ratio of the mass of water m_W contained in a solid to the mass of dry basis m_S, expressed in Eq. (1):

$$u = \frac{m_W}{m_S} \quad (1)$$

where u – water content, dry basis g g^{-1}; m_W – mass of water, g; m_S – mass of dry basis, g.

Water content, wet basis w is the ratio of the mass of water m_W contained in a solid to the mass of the moist solid $m = m_S + m_W$, expressed in Eq. (2):

$$w = \frac{m_W}{m} 100 \quad (2)$$

where w – water content, wet basis, %.

Changes of the water content du during the time difference dt describe the drying rate N expressed in Eq. (3):

$$N = \frac{\Delta u}{\Delta t} \quad (3)$$

where N – drying rate, g g^{-1}h^{-1}; t – time, h.

The colour of the cloves was measured at intervals of several days. The colour was evaluated according to the CIELAB system where colour attributes lightness (L* value), redness (a* value) and yellowness (b* value) were measured five times of each fresh sample and during the whole process of black garlic preparation at intervals of several days. The instrument used for this research, Spectrophotometer CM-600d Konica Minolta, was first calibrated. Calibration is based on the black (L* = 0) and white (L* = 100) standards.

The obtained results of the colour range coordinates of tested garlic samples were processed by Excel software and verified by statistical software Statistica 12 (*ANOVA* and *TUKEY HSD Test*) to determine whether the differences are significant at the significance level of 0.05.

RESULTS AND DISCUSSION

The kinetics of the black garlic preparation process described by the curves calculated according to equations (1), (2) and (3) are shown in Fig. 1–3.

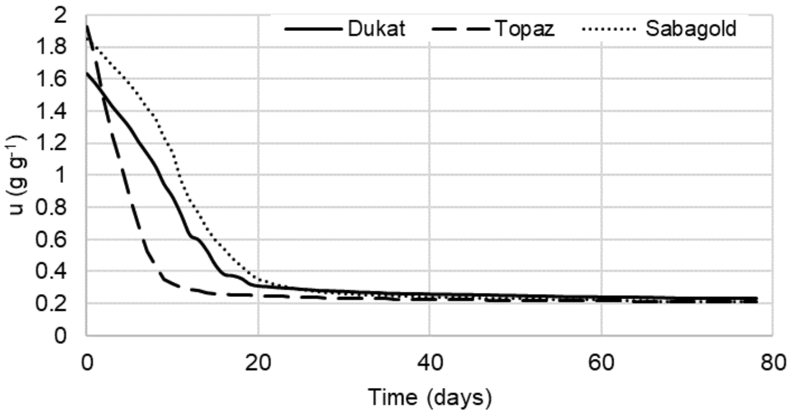

Figure 1. Water content, dry basis u (g g^{-1}) of garlic samples during the processing.

Fresh garlic processing into black garlic was uneven and certain differences existed between the investigated varieties. The intensive decrease of water content, dry basis u (g g^{-1}) during the first 20 days from values of 1.6 to 1.9 (g g^{-1}) to below 0.4 (g g^{-1}) was fastest in the Topaz variety, when it decreased below 0.4 (g g^{-1}) after only 9 days (Fig. 1).

These changes are also matched by changes in water content, wet basis w (%), the course of which is shown in Fig. 2. From the original values of w = 62 to 66%, within 20 days the water content, wet basis, dropped below 30%, and in the Topaz variety even below 20%.

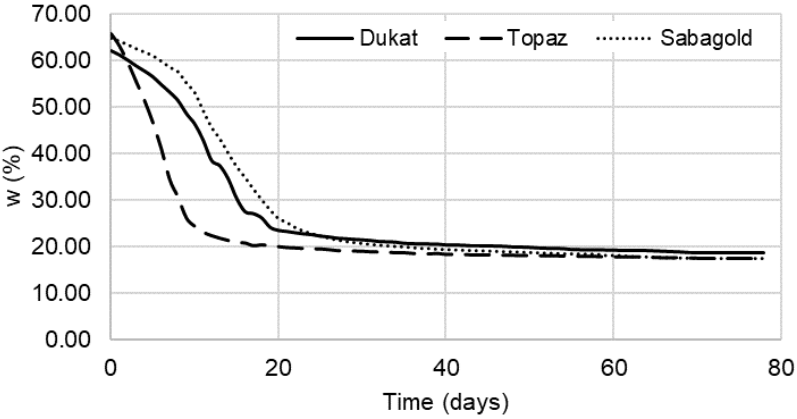

Figure 2. Water content, wet basis w (%) of garlic samples during the processing.

The drying rate (specific weight change due to water loss) of garlic N (g $g^{-1}h^{-1}$) is shown in Fig. 3. After 30 days, the N values (g $g^{-1}h^{-1}$) decreased significantly, therefore only this period is shown in Fig. 3. The highest N values were reached in the Topaz variety within the first 3 days. Overall, the N curves show that the first 30 days are the most important in terms of weight and moisture changes.

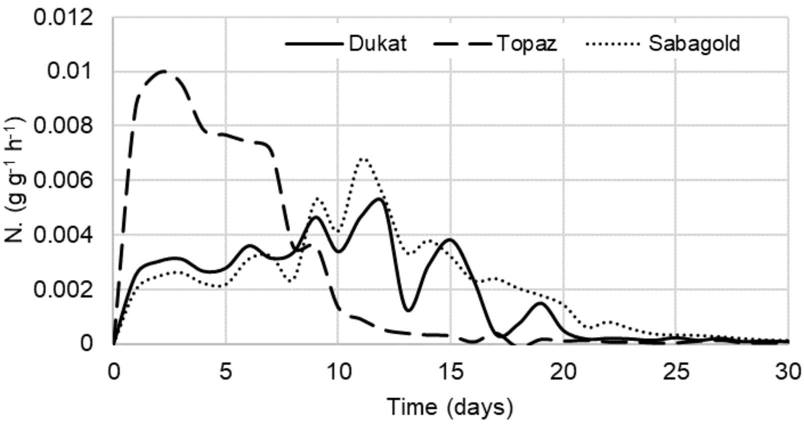

Figure 3. Drying rate N (g $g^{-1}h^{-1}$) of garlic samples during the first 30 days of processing.

The results of the lightness L* in Table 1 show that the measured samples of individual varieties of fresh garlic differ significantly. They also differ during processing into black garlic at 60 °C, only on the 54th day of processing were the differences in L* insignificant.

Tables 2 and 3 show the colour specifications a* and b*. Greenness (-a*) was found in all fresh garlic samples (Table 2). The most pronounced greenness was measured in the Sabagold variety (-2.63 ± 0.13). In the following days of processing, the influence of the Maillard reaction became apparent and all samples lost their greenness and turned into shades of redness, this shade was most intense on the 9th day in the Dukat variety (a* = 8.73 ± 0.13). On the 54th day of treatment, the differences in a* were insignificant. Yellowness (b*) was highest in the Dukat fresh garlic (22.12 ± 0.24), the Topaz and Sabagold varieties differed only insignificantly (Table 3). During the preparation of black garlic, differences in yellowness between the varieties alternated.

Tables 4–6 evaluate the results of lightness L* and colour specifications a* and b* throughout the entire measurement of the conversion of fresh garlic into black garlic for all varieties. A significant decrease in lightness, i.e. darkening, occurred on the 9th day for the Dukat varieties (ΔL* = 45.33) and Topaz (ΔL* = 48.06), while the Sabagold variety experienced a less pronounced darkening on the 9th day (ΔL* = 35.13). From the 26th to the 33rd day, a further significant

Table 1. Comparison of average values and standard deviation of the lightness L* of the investigated garlic varieties Dukat, Topaz and Sabagold on individual measured days

Day	Dukat	L*± SD Topaz	Sabagold
0	80.39 ± 0.08^{a}	78.29 ± 0.07^{b}	83.64 ± 0.17^{c}
9	35.06 ± 0.21^{a}	30.23 ± 0.25^{b}	48.51 ± 0.05^{c}
26	27.61 ± 0.19^{a}	28.52 ± 0.09^{a}	23.85 ± 1.48^{b}
33	29.80 ± 0.01^{a}	29.58 ± 0.04^{b}	26.09 ± 0.12^{c}
54	28.91 ± 1.18^{a}	28.68 ± 0.36^{a}	27.91 ± 1.79^{a}
78	27.47 ± 0.60^{a}	29.09 ± 0.45^{b}	28.72 ± 0.65^{b}

SD – standard deviation. $^{a, b, c}$ Identical superscript letters for numbers in a row indicate that there is no statistically significant difference between measured values.

Table 2. Comparison of average values and standard deviation of the colour shades, a* of the investigated garlic varieties Dukat, Topaz and Sabagold on individual measured days

Day	Dukat	a*± SD Topaz	Sabagold
0	-1.21 ± 0.05^{a}	-1.41 ± 0.01^{b}	-2.63 ± 0.13^{c}
9	8.73 ± 0.13^{a}	6.68 ± 0.51^{b}	6.63 ± 0.09^{b}
26	4.95 ± 0.44^{a,b}	6.52 ± 0.23^{a}	3.19 ± 2.62^{b}
33	5.38 ± 0.02^{a}	6.87 ± 0.09^{b}	6.46 ± 0.29^{c}
54	5.25 ± 2.03^{a}	5.35 ± 0.17^{a}	6.73 ± 0.35^{a}
78	2.13 ± 0.56^{a}	4.80 ± 0.50^{b}	3.96 ± 0.32^{b}

SD – standard deviation. $^{a, b, c}$ Identical superscript letters for numbers in a row indicate that there is no statistically significant difference between measured values.

Table 3. Comparison of average values and standard deviation of the colour shades, b* of the investigated garlic varieties Dukat, Topaz and Sabagold on individual measured days

Day	Dukat	b*± SD Topaz	Sabagold
0	22.12 ± 0.24^{a}	21.21 ± 0.10^{b}	21.30 ± 0.58^{b}
9	11.85 ± 0.27^{a}	7.70 ± 0.43^{b}	22.52 ± 0.16^{c}
26	5.22 ± 0.79^{a}	7.90 ± 0.14^{b}	3.16 ± 2.24^{a}
33	5.29 ± 0.03^{a}	7.51 ± 0.03^{b}	5.93 ± 0.21^{c}
54	4.90 ± 1.21^{a}	7.10 ± 0.06^{b}	7.20 ± 1.45^{b}
78	3.15 ± 0.35^{a}	6.39 ± 0.16^{b}	4.48 ± 1.34^{a}

SD – standard deviation. $^{a, b, c}$ Identical superscript letters for numbers in a row indicate that there is no statistically significant difference between measured values.

decrease in lightness occurred for Dukat (ΔL* = 7.45), Topaz (ΔL* = 1.71) and Sabagold (ΔL* = 24.66). Since this period, the lightness values L* have changed, and the measurement results have fluctuated alternately, which was influenced by small differences in the measured clove samples in the bulbs.

Greenness (-a*) changed from the 9th day to a redness (a*) whose saturation gradually decreased in Dukat (from a* = 8.73 to 2.13), Topaz (from a* = 6.68 to 4.80) and Sabagold (from a* = 6.63 to 3.96). Yellowness (b*) decreased from the 9th day, Dukat (from b* = 22.12 to 3.15), Topaz (from b* = 21.21 to 6.39) and Sabagold (from b* = 21.30 to 4.48). Also, the values of the colour specifications a* and b* showed occasional fluctuations in the measured values due to small differences in the measured clove samples in the bulbs.

Table 4. Colour range coordinates (L*, a* and b* mean values with SD) of tested garlic variety Dukat samples on individual measured days

Day	L*± SD	a*± SD	b*± SD
0	80.39 ± 0.08[a]	-1.21 ± 0.05[a]	22.12 ± 0.24[a]
9	35.06 ± 0.21[b]	8.73 ± 0.13[b]	11.85 ± 0.27[b]
26	27.61 ± 0.19[c]	4.95 ± 0.44[c]	5.22 ± 0.79[c]
33	29.80 ± 0.01[d]	5.38 ± 0.02[c]	5.29 ± 0.03[c]
54	28.91 ± 1.18[d]	5.25 ± 2.03[c]	4.90 ± 1.21[c]
78	27.47 ± 0.60[c]	2.13 ± 0.56[d]	3.15 ± 0.35[d]

SD – standard deviation. [a, b, c, d] Identical superscript letters for numbers in a column indicate that there is no statistically significant difference between measured values.

Table 5. Colour range coordinates (L*, a* and b* mean values with SD) of tested garlic variety Topaz samples on individual measured days

Day	L*± SD	a*± SD	b*± SD
0	78.29 ± 0.07[a]	-1.41 ± 0.01[a]	21.21 ± 0.10[a]
9	30.23 ± 0.25[b]	6.68 ± 0.51[b]	7.70 ± 0.43[b]
26	28.52 ± 0.09[c]	6.52 ± 0.23[b]	7.90 ± 0.14[b]
33	29.58 ± 0.04[d]	6.87 ± 0.09[b]	7.51 ± 0.03[b,c]
54	28.68 ± 0.36[c]	5.35 ± 0.17[b,c]	7.10 ± 0.06[c]
78	29.09 ± 0.45[c,d]	4.80 ± 0.50[c]	6.39 ± 0.16[d]

SD – standard deviation. [a, b, c, d] Identical superscript letters for numbers in a column indicate that there is no statistically significant difference between measured values.

Table 6. Colour range coordinates (L*, a* and b* mean values with SD) of tested garlic variety Sabagold samples on individual measured days

Day	L*± SD	a*± SD	b*± SD
0	83.64 ± 0.17[a]	-2.63 ± 0.13[a]	21.30 ± 0.58[a]
9	48.51 ± 0.05[b]	6.63 ± 0.09[b,c,d]	22.52 ± 0.16[a]
26	23.85 ± 1.48[c]	3.19 ± 2.62[b,d]	3.16 ± 2.24[b]
33	26.09 ± 0.12[c,d]	6.46 ± 0.29[b,c,d]	5.93 ± 0.21[b,c]
54	27.91 ± 1.79[d,e]	6.73 ± 0.35[b]	7.20 ± 1.45[c]
78	28.72 ± 0.65[e]	3.96 ± 0.32[b,c,d]	4.48 ± 1.34[b,c]

SD – standard deviation. [a, b, c, d, e] Identical superscript letters for numbers in a column indicate that there is no statistically significant difference between measured values.

CONCLUSIONS

This article presents the results of research focused on the heat treatment of garlic (*Allium sativum*) and its transformation into black garlic. The results of measuring the heat process of garlic processing at a temperature of 60 °C showed that the decrease of water content, wet basis w (%), from the original values w = 62 to 66% to below 30% was within 20 days for the Dukat and Sabagold varieties, and below 20% for the Topaz variety.

The results of measuring the colour of garlic cloves showed that there are differences between the varieties in the initial lightness and during the darkening and colour change. To achieve the final dark colour in this process, 26 days were sufficient at a temperature of 60 °C.

Further research would be appropriate to focus on more detailed monitoring of the physical properties of garlic during the process of transformation of fresh garlic into black garlic, especially over the course of 30 days, to verify the processing even at different temperatures and to expand the number of garlic varieties studied.

Experiments could also be focused on using different methods of sealing garlic to prepare black garlic in different containers or other packaging.

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Integrating human factors into occupational accident investigation: a literature review of methodologies and their applications

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Abstract. Introduction: Accident investigation is essential in safety management, aiming to identify causes and prevent recurrence. Despite various methodologies, gaps remain in information collection and human factors integration. Since data collection is the foundation of investigations, deficiencies can compromise conclusions. This study reviews literature on human factors, focusing on their integration into investigation of occupational accidents. The review explores the nature of human factors and investigation methods that address cognitive, psychological, and organisational dimensions. The study also proposes an integrated investigation flow that combines these methodologies to enhance the accuracy and effectiveness of accident investigations.
Methods: A literature review was conducted using academic databases. Keywords included 'accident investigation', 'human factors', and 'occupational safety'. Inclusion criteria focused on articles, books, and reports from 1990 to 2025, covering topics of interest and safety-critical industries. Relevant literature was screened and analysed based on its contributions to the research topic. Key investigation methodologies were analysed for their strengths and limitations.
Results: The study revealed a multitude of methodologies available, each with its own set of strengths and limitations. HFACS, HEART and FMEA methods were analysed for their potential to systematically integrate human factor. While these methodologies demonstrate significant promise, their implementation remains inconsistent due to challenges related to training, organisational culture, and resource allocation.
Conclusions: This review emphasizes the importance of integrating human factors into accident investigation methodologies to enhance workplace safety. While traditional methods remain valuable for their accessibility, systemic approaches are essential for addressing complex socio-technical systems. Future efforts should prioritize investigator training and promotion of positive organisational culture to mitigate human factor challenges and improve investigative outcomes.

Key words: occupational accident investigation, human factors, investigation models, safety-critical industries.

INTRODUCTION

Production industry has witnessed significant advancements in automation and technological innovation over recent decades, which have led to increased operational efficiency and a marked reduction in manual labour-intensive processes. Despite these achievements, occupational accidents remain a persistent concern, with significant impact on human resources and productivity of entities (Laske et al., 2022; Estudillo et al., 2024). Studies indicate that even in automated industries, human factors continue to play a significant role in workplace incidents, often surpassing technical failures. (Dekker, 2006; Fernández-Muñiz et al., 2017; Pačaiová et al., 2021).

Data from the Latvian State Labour Inspectorate further supports these conclusions. It reveals that unsafe human actions are a significant cause of occupational accidents. These actions include non-compliance with safety regulations, failure to use safety equipment, and working under the influence of alcohol. Although the proportion of accidents caused by these actions has declined from 33% in 2021 to 18% in 2023, it remains a critical factor in workplace safety. Deficiencies in work organisation, such as insufficient training, poor supervision, and inadequate task control, have also played a major role in workplace accidents. These deficiencies peaked at 35% in 2022. Traffic rule violations have consistently contributed to workplace accidents, accounting for 25% in 2023. Although less prominent, unsatisfactory workplace conditions, such as the use of damaged equipment or inadequate safety tools, were cited as causes of 7% of accidents in 2023. Additionally, workplace violence emerged as a cause for the first time in 2023, accounting for 4% of accidents. The analysis of occupational accident causes from 2019 to 2023 in Latvia supports the conclusion that human factors remain a predominant cause of workplace incidents (Latvian State Labour Inspectorate, 2024).

Occupational accidents were once viewed as a linear sequence of events. Today, they are recognized as complex errors resulting from interactions between human, technological, and environmental factors, emphasizing the need for effective human factors management (Dekker, 2006; Salguero-Caparros et al., 2015). However, integrating human factors into occupational accident investigations remains challenging due to limited expertise, inconsistent methodologies, and insufficient training (Burban, 2016). As emphasised by Randle, human factors play a fundamental role in process safety management within a system, which includes the following elements: people, tasks, equipment and interfaces, environment, organisations, in which they work, and location in the world (Randle, 2021).

This challenge is compounded by the lack of a unified definition or understanding of what constitutes 'human factors'. Researchers and practitioners often interpret human factors differently, depending on their disciplinary backgrounds or the specific contexts in which they operate. The aim of this study is to explore integration of human factors into occupational accident investigations and answer following research questions:

- How have definitions and concepts of human factors evolved, and what is their relevance to occupational accident investigations today?
- How are human factors integrated into occupational safety investigations?
- What investigation methods are effective in identifying human factor in occupational accident investigations?

METHODS

This study employed a systematic literature review approach to identify and analyse relevant research on integrating human factors into occupational accident investigations. Scopus database was queried to search for sources written in English and published between 1995 and 2025. Keywords used in the search strategy included combinations of terms ‘accident investigation’, ‘human factors’, and ‘occupational safety’. Boolean operator (AND) was employed to refine the search queries.

The inclusion criteria were:

- articles, books, and reports published between 1995 and 2025;
- literature focusing on safety-critical manufacturing industries;
- publications in English language;
- Open access sources.

Exclusion criteria included studies unrelated to occupational accidents, focused solely on technical or engineering failures without considering human factors. The search initially identified 144 potentially relevant studies. Studies, that did not meet the inclusion criteria, were excluded. After screening for relevance, 78 studies were selected for analysis.

Among the wide range of investigation models identified, three methodologies - Human Factors Analysis and Classification System (HFACS), Human Error Assessment and Reduction Technique (HEART), and Failure Mode and Effects Analysis (FMEA) - emerged as particularly prominent in terms of relevance, theoretical grounding, and practical application to occupational safety contexts. These three frameworks were thus selected for focused analysis, evaluating their strengths, limitations, and application to human factors integration in occupational accident investigations.

The collected information was analysed to address the research questions outlined in this study. Specifically, the data were categorized into three primary themes: (1) human factors within occupational environment setting, (2) parameters employed to evaluate human factors, and (3) human factors in accident investigation.

By organizing the review into these topics, the analysis was aimed to explore current methodologies and propose a flow that improves accident investigation.

RESULTS

Human Factors within occupational environment setting

Human factors refer to psychological, cognitive, physical, and organisational elements that influence human performance in workplace settings (Kroemer et al., 2010; Reyes et al., 2015). These factors shape how individuals interact with tasks, equipment, and their working environment, impacting safety outcomes. In accident investigations, human factors provide a crucial perspective for understanding not only immediate causes but also underlying organisational, cognitive, and behavioural issues that contribute to incidents (Dekker, 2006; Hollnagel, 2014).

Human factors can be categorized into three categories. Psychological factors: emotions, attitudes, and motivations that influence behaviour and decision-making (Gervasi et al., 2022). Cognitive factors: mental workload, situational awareness, and information processing that impact task performance (Endsley, 1997; Nicoletti & Padovano, 2019). Organisational factors: leadership, training quality, communication, and safety culture that shape workplace environments (Hale et al., 2015; Randle, 2021).

The concept of human factors has evolved significantly over time. Early definitions defined human factors as the study of human interactions with machines and systems, emphasizing the need to adapt equipment to human capabilities rather than forcing individuals to adjust to poorly designed tools (Chapanis et al., 1949). Fitts (1951) introduced 'man-machine system' concept, highlighting the importance of interface design in reducing errors. This concept was later modified by Singleton to include cognitive psychology, emphasizing decision-making and problem-solving as critical components of human-machine interaction (Singleton, 1967).

A significant shift in human factors theory occurred with the introduction of systemic approaches. Senders & Moray (1977) defined human factors as a discipline aimed at improving system design to accommodate human strengths and compensate for weaknesses, highlighting the importance of creating environments that proactively prevent human errors. Human-centred design concept emerged, emphasizing usability and user experience as key components of human factors. This approach encouraged system designers to focus on human capabilities and limitations, ensuring that systems are tailored to fit human needs rather than forcing users to adapt to poorly designed environments (Norman, 1986). Reason (1990) further advanced this systemic perspective by introducing the Swiss Cheese Model, which conceptualizes human error as a symptom of deeper organisational issues. This model illustrates how multiple layers of defence (such as supervision, training, or regulations) may have weaknesses, which, when aligned, create conditions for an accident to occur. This model remains a cornerstone in understanding human error and is widely applied across industries (Perneger, 2005; Larouzée, 2017; Larouzee & Le Coze, 2020).

Contemporary definitions recognize the role of psychological and organisational aspects. This view has encouraged a shift away from focusing solely on individual errors to recognizing the systemic factors that shape employee behaviour. Hollnagel (2014) advocates for understanding how successful human performance is maintained, emphasising proactive strategies that identify and strengthen conditions that promote safe work practices. Whereas Randle (2021) points that human factors include not only individual performance but also interactions with tasks, equipment, work environment, and organisational structures. The modern understanding of ergonomics was significantly shaped by the International Ergonomics Association (IEA) under the presidency of Ian Noy. In 2000, the IEA formally adopted a definition that defined ergonomics as both a scientific discipline and practical profession, acknowledging its interdisciplinary nature and application across diverse sectors. Noy (2018) highlighted that this definition was crucial in uniting conflicting perspectives on whether ergonomics should be regarded as an academic discipline or a practical field. This definition remains one of the most important in modern safety research (Noy &William duPont IV, 2018).

Recent research by de Nobile et al. (2024) explored human factors in human-robot collaboration, addressing psychological, cognitive, and physical dimensions, emphasising the importance of interdisciplinary approaches to enhance productivity and safety in industrial settings.

As noted by Roja & Kaļķis (2020), term ‘human factors’ is often used to describe the ability of individuals to collaborate with one another, interact with workplace equipment and tools, and engage with management systems while considering workplace culture. The modern understanding of human factors has broadened significantly, involving not only ergonomic and physical aspects but also distinguishes between psychological, cognitive and physical human factors. Human factors refer to psychological, cognitive, physical, and organisational elements that influence human performance in workplace settings (Reyes et al., 2015). These factors shape how individuals interact with tasks, equipment, and their working environment, impacting safety outcomes. In accident investigations, human factors provide a crucial perspective for understanding not only immediate causes but also underlying organisational, cognitive, and behavioural issues that contribute to incidents (Dekker, 2006; Ferry, 2014; Hollnagel, 2014).

Human factors encompass psychological, cognitive, physical, and organisational elements that influence workplace safety (Kroemer et al., 2010; Reyes et al., 2015). While psychological and cognitive aspects are closely related, this review intentionally separates them to reflect distinct influences - psychological factors such as emotions and motivation, and cognitive factors such as mental workload and information processing (Hollnagel, 2014; Nicoletti & Padovano, 2019; Sætren et al., 2024). Although the physical domain of ergonomics is widely acknowledged, particularly by the IEA (2000), this review focuses on psychological, cognitive, and organisational dimensions due to their direct relevance to behavioural and systemic causes in accident investigations. Therefore, according to modern understanding, human factors can be categorized into three key dimensions (Table 1).

Human factors are central to the effective functioning of work systems, serving as the interface between employees, technology, and organisational structures, but variability of definitions and their understanding pose challenges for safety management (Hale et al., 2015). Despite growing recognition of human factors in safety-critical industries, traditional accident investigation methodologies still tend to prioritize technical failures over human and organisational errors (Dekker, 2006; Dien et al., 2012; Read, et al., 2021). Many investigations focus on immediate, tangible causes, such as mechanical malfunctions, rather than the underlying cognitive and organisational factors that may have contributed to the event.

A review of accident reports within industrial settings revealed that investigators often struggle to differentiate between active human errors and latent organisational conditions. For instance, in workplace incidents involving procedural violations, reports frequently attribute the event to ‘worker negligence’ without examining whether poor safety culture, inadequate training, or excessive workload were contributing factors (Stemn et al., 2019). This indicates a need for better integration of systemic human factors models.

Table 1. Key Dimensions and Elements of Human Factors in Occupational Safety

Human factor dimension	Key element	Description
Psychological human factors	Emotions, attitudes	Frustration, anxiety, or overconfidence can impair judgment and increase the risk of incidents (Gervasi et al., 2022)
	Motivations behaviour	Employee motivation levels affect risk-taking behaviours, compliance with safety procedures, and task performance (Reyes et al., 2015)
	Awareness	Ensures employees recognize and respond to potential hazards, particularly critical in environments requiring rapid decision-making, where distractions and mental overload may compromise safety (Endsley, 1997; Nicoletti & Padovano, 2019; He et al., 2021), enhancing awareness through training and real-time feedback mechanisms can significantly reduce the likelihood of incidents (Naderpour et al., 2015)
	Trust	Important factor in team dynamics and use of safety systems. Employees who lack trust in their peers, supervisors, or organisational processes may hesitate to report risks, ultimately increasing the potential for errors (Arkin et al., 2012; Judeh, 2016)
Cognitive factors	Mental workload	Excessive workload can reduce focus, impair memory, and limit the ability to identify and respond to hazards effectively (Carayon, 2006)
	Information processing	Is critical in environments where complex decisions must be made quickly (Nicoletti & Padovano, 2019).
	Stress, fatigue	Can impair judgment, reduce attention, and increase error likelihood, especially in demanding or high-risk environments (Sneddon et al., 2013).
Organisational factors	Leadership, supervision	Effectiveness has significant influence on safety culture, encouraging compliance with procedures, and ensuring employees feel supported (Randle, 2021).
	Training, communication	Shape workplace environments (Randle, 2021; Hale et al., 2015)
	Workplace culture	If positive encourages employees to report risks, engage in safe practices, and collaborate effectively to improve workplace safety (Hale et al., 2015).

Integration of human factors into occupational safety investigations

Prior to integrating human factors into occupational accident investigations, it is essential to establish clear definitions of both ‘accident’ and ‘occupational safety’. Early definitions, such as Heinrich’s (1936), described accidents as ‘unplanned and uncontrolled events involving an object, person, or reaction that results in or has the potential to result in injury’. However, modern interpretations have challenged this definition, arguing that many accidents are foreseeable and preventable with adequate safety measures and systems (Hollnagel, 2004; Dekker et al., 2011).

Occupational safety refers to the measures and regulations implemented to ensure the well-being and protection of workers in their workplace. It encompasses a wide range of topics, all aimed at promoting health and well-being in the workplace. The goal of occupational safety to foster a safe and healthy work environment, which also protects co-workers, family members, employers, customers, and others who might be affected by the workplace environment (Kiersma, 2014). Understanding these definitions is important for effective integration of human factors into occupational accident investigations, as it allows for a comprehensive approach that considers both individual behaviors and systemic influences on workplace safety.

To incorporate human factors effectively into occupational accident investigations, researchers advocate for frameworks that encompass cognitive, psychological, and organisational dimensions. For instance, stress, fatigue, and mental workload are increasingly recognized as significant contributors to occupational accidents (Dekker, 2002; Dekker et al., 2011). Stress-induced errors frequently stem from inadequate safety climates and lead to poor situational awareness, delayed responses, and decision-making lapses (Moura et al., 2016). Similarly, Liao et al. (2021) demonstrated that excessive cognitive demands impair workers' ability to respond effectively to dynamic work environments, emphasising the need for cognitive workload management in safety investigations.

Human Factors Analysis and Classification System (HFACS) has emerged as one of the widely used frameworks in accident investigations, particularly for its ability to systematically identify and categorise human errors. Initially developed for aviation safety (Materna et al., 2023), HFACS has later been adapted for use in occupational safety to determine the root causes of workplace accidents (Omole & Walker, 2015; Ergai et al., 2016; Hulme et al., 2020). Numerous studies have demonstrated how HFACS can be applied in high-risk industries (Omole & Walker, 2015; Baldissone et al., 2019; Guo et al., 2023; Maternová & Materna, 2023; Wang et al., 2025). HFACS is structured according to four pillars: organisational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts themselves, allowing for a multi-layered analysis of human and systemic factors contributing to accidents (Guo et al., 2023; Wang et al., 2025). Research by Leveson et al. (2009) investigated how HFACS helps to identify latent conditions that can lead to unsafe actions. Moreover, HFACS could serve to provide input for accident prevention strategies (Wang et al., 2025), Comprehensive analysis of occupational accidents using HFACS, found that poor communication, inadequate training, and fatigue were among the most recurrent preconditions for unsafe acts (Baldissone et al., 2019). Investigation process conducted by applying HFACS method can be illustrated as follows (Fig. 1).

Another applicable method for integrating human factors into occupational accident investigation is Human Error Assessment and Reduction Technique (HEART) which is quantitative approach for evaluating the likelihood of human errors and their potential impact within complex systems. Its application in occupational accident investigations helps to quantify human error probabilities and provides a framework for understanding how these errors influence organisational safety culture and employee behaviour (Aliabadi et al., 2024; Musavi, 2024). HEART operates by assigning error probabilities to specific tasks based on influencing factors known as Error Producing Conditions (EPCs), such as stress, complexity, and lack of training (Musavi, 2024). By categorising tasks and their associated risks, HEART provides investigators with a structured methodology to identify weaknesses in work systems that may contribute to accidents (Kandemir & Celik, 2021). Investigation process conducted by applying HEART method can be illustrated as follows (Fig. 2).

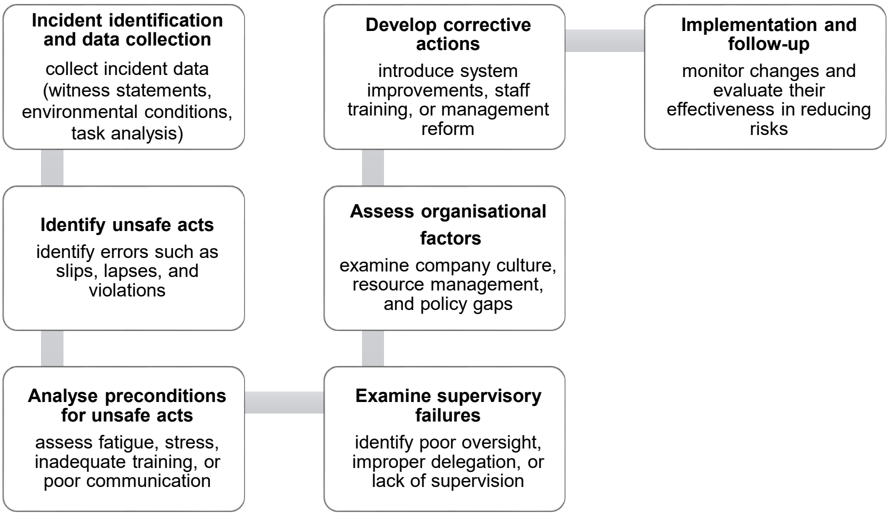

Figure 1. HFACS investigation process flowchart.

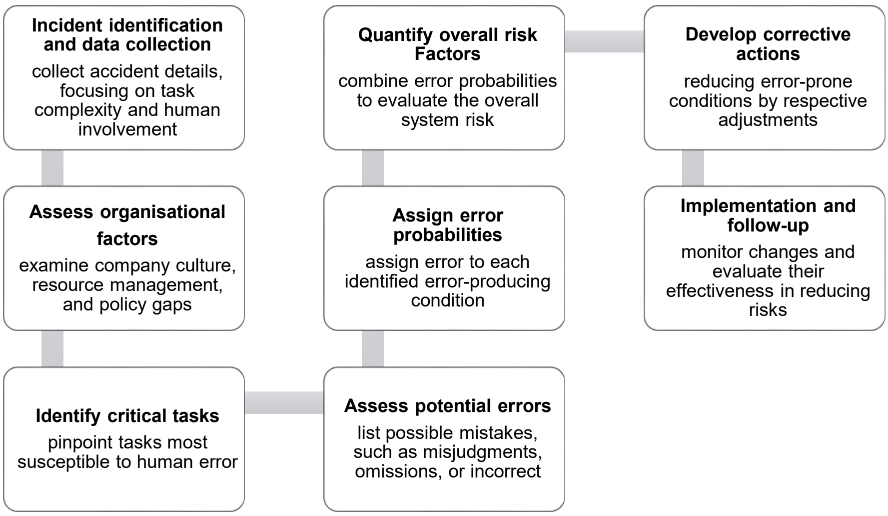

Figure 2. HEART investigation process flowchart.

Another method is Failure Mode and Effects Analysis (FMEA) which is structured, systematic methodology widely utilized to evaluate potential failure modes within systems and processes, analyse their causes and effects, and prioritise corrective actions to mitigate risks. In the context of occupational accident investigation, FMEA provides framework to identify error types and their impacts on investigation reports, it points human factors that contribute to deficiencies in accident analysis and documentation (Stamatis, 2014; Sutton, 2014; Chakrabarty et al., 2016; Huang et al., 2020).

Study by Liu et al. (2024) illustrates the use of FMEA in identifying latent human errors that influence accident outcomes. It was revealed that insufficient communication and procedural violations significantly affect the accuracy of investigation reports. By dissecting accident reports using FMEA, researchers can categorize human factors into several dimensions, including cognitive errors, procedural lapses, and organisational deficiencies. Huang et al. (2020) found that incorporating human factors into FMEA facilitated the identification of errors in decision-making processes during high-stress situations, a common cause of incomplete or biased accident investigations.

Additionally, FMEA, being a highly variable method, can be utilised in various industrial contexts. It was demonstrated that the method could uncover patterns of errors specific to industries such as construction and manufacturing, where accidents are frequently attributed to misjudgements or non-compliance with safety standards Liu et al. (2024). Another significant advantages of FMEA in accident investigations is its potential to improve the quality of reports by addressing gaps in data collection and analysis. Researches showed that integrating FMEA into post-accident investigations led to more detailed root cause analyses, reducing ambiguity in identifying contributing factors (Huang et al., 2020; Liu et al., 2024). Investigation process conducted by applying FMEA method can be illustrated as follows (Fig. 3).

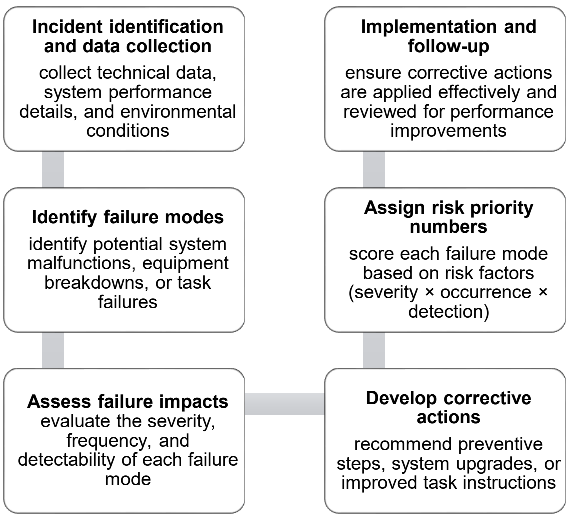

Figure 3. FMEA investigation process flowchart.

Each method follows a structured process that begins with gathering evidence and concludes with the implementation of corrective actions. While HFACS, HEART, and FMEA each provide distinct approaches to analysing human factors, they share a common objective: identifying key factors that contribute to incidents and ensuring effective corrective actions are developed to prevent recurrence.

Based on the analysis of methodologies discussed in the reviewed studies, the author has developed a table (Table 2) that presents a comparative overview of these methodologies and aims to provide a guide selecting the most suitable approach for specific investigation needs.

Table 2. Comparison of methodologies for integrating human factors into occupational safety investigations

Method	Purpose	Strengths	Limitations	Key findings
HFACS	Systematic identification and classification of human errors	Identifying latent conditions and systemic issues applicable across industries, including high-risk	Requires detailed investigator training; may overlook environmental and cultural factors	Identifies latent and active errors for safety improvements
HEART	Quantitative assessment of human error probabilities and impacts	Useful for complex systems with multiple error sources	Relies heavily on accurate data collection subject to evaluator bias	Highlights high-risk tasks and error-prone conditions for targeted interventions
FMEA	Analysis of failure modes, their causes, and effects.	Flexible and applicable across diverse industries; focuses on proactive error identification	Resource-intensive require experienced teams for effective use	Identifies error types and improves the quality of accident investigation reports

Studies have shown that integrating HEART into occupational accident investigations can significantly enhance the identification of root causes and provide a more comprehensive understanding of how human and organisational factors interact (Ginting & Tambunan, 2016; Williams & Bell, 2016). Moreover, HEART can be integrated with other methodologies like HFACS (Human Factors Analysis and Classification System) to provide a more holistic view of accident causation (Aliabadi, 2021; Kandemir & Celik, 2021; Kang et al., 2021; Octaviani & Arifin, 2024).

Integrating these methodologies can significantly enhance the identification of root causes in occupational accident investigations. Each method offers unique perspectives: HEART focuses on quantifying human error probabilities, HFACS provides a framework for analysing human and organisational factors, and FMEA systematically identifies potential failure modes and their impacts. When used jointly, these methods complement each other, offering a more comprehensive understanding of accident causation (Liou et al., 2022; Meng & Lu, 2022; Gangadhari et al., 2024).

Based on the literature study, the author proposes the following structured scheme for integrating human factors into occupational accident investigations. This scheme combines key elements from HFACS, HEART, and FMEA frameworks, addressing their strengths while mitigating their limitations (Fig. 4).

[Initial Response] → [Data Collection] → [Preliminary Analysis]
↓
[HFACS Analysis] → [HEART Analysis] → [FMEA Analysis]
↓
[Root Cause Analysis]
↓
[Development of Corrective Actions] → [Implementation]
↓
[Follow-up and Monitoring]
↓
[Knowledge Sharing and Training]

Figure 4. Integrated Process Flow for Occupational Accident Investigation Incorporating Human Factors Methodologies.

DISCUSSION

The findings of this review highlight the complex nature and role of human factors in both the occurrence and prevention of occupational accidents. While traditional investigation methods have long emphasized technical failures, this study examined the importance of adopting approach that considers cognitive, psychological, and organisational dimensions. Human factors are complex, combining psychological, cognitive, and organisational influences that interact in dynamic ways. As research has demonstrated, human behaviour is rarely the result of a single cause. This complexity requires investigation to extend beyond technical causes and explore deeper systemic issues.

The review discovered that systemic methods can be effective in capturing the complexity of human factors, and combination of those can enhance investigation outcomes. Despite their potential, several barriers hinder the successful application of these models. The complexity of systemic approaches often requires specialized training and expertise, which may limit adoption in industries with limited resources. Furthermore, organisations that rely heavily on traditional investigative practices may be resistant to transitioning toward human factor-centred approaches

To improve the integration of human factors into occupational accident investigations, several steps could be recommended. First, developing clear, universal guidelines for applying HFACS, HEART, and FMEA can improve consistency and ensure investigators effectively identify systemic factors alongside technical causes. Second, improving investigator training is critical to building competence in identifying psychological, cognitive, and organisational contributors to workplace accidents. Third, organisations should establish structured reporting systems that capture detailed information on environmental conditions, workplace behaviour, and organisational processes. Improved data quality is crucial for identifying systemic issues and enhancing investigation accuracy. Moreover, promoting a positive safety culture within organisations can encourage employees to report risks, unsafe behaviours, and systemic concerns.

Based on the reviewed methodologies, author proposes a simplified investigation flow that combines the strengths of HFACS, HEART, and FMEA. The proposed approach begins with data collection and preliminary analysis, followed by layered application of HFACS to identify systemic and behavioural issues, HEART to assess human error probabilities, and FMEA to prioritise failure modes. These tools are used together to uncover root causes and inform corrective actions. Though this hybid approach has significant limitations such as time constraint and knowledge of the methods. Therefore, future efforts should focus on developing clear investigation guidelines, improving investigator training, and promoting comprehensive data collection practices to support successful implementation.

CONCLUSIONS

This review has shown that the concept of human factors has evolved from a narrow focus on ergonomics to a broader, multidimensional perspective that includes psychological, cognitive, organisational, and physical elements. This shift is crucial for accurately analysing the root causes of occupational accidents. The integration of human factors into occupational safety investigations is advancing, with increasing emphasis on systemic approaches that account for both individual behaviour and organisational context. Among the reviewed methods, HFACS, HEART, and FMEA emerged as particularly effective in identifying and categorising human and organisational factors. Their structured frameworks help reveal both active and latent conditions, thereby improving the quality and impact of accident investigations.

The review highlighted several areas that would need further attention and future research to enhance the integration of human factors into occupational accident investigations which are standardization of methodologies by developing universal guidelines, investigator training and educations to enhance competency of investigators.

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An overview of the technical and economic opportunities for biogas-based hydrogen production in Latin America

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Abstract. The growing need for sustainable energy solutions has intensified interest in alternative sources to reduce reliance on fossil fuels. Latin America, with its abundant biomass resources from agricultural and industrial activities, offers significant potential for renewable energy generation. Biogas, derived from the anaerobic digestion of organic waste, presents a viable energy carrier and a promising feedstock for hydrogen production, a key component in global decarbonization efforts. Despite these opportunities, the adoption of biogas-based hydrogen production in Latin America remains limited due to high capital costs, technological challenges, inadequate infrastructure, and weak policy frameworks. This study provides a comprehensive analysis of the region's potential by assessing biomass availability, technological pathways, and economic feasibility through data from research institutions and scientific literature. Technologies such as steam methane reforming and emerging biological processes are evaluated, alongside country-specific regulatory frameworks. Findings highlight those countries with strong agricultural sectors, such as Brazil, Argentina, and Colombia, hold high potential. However, economic challenges endure, with substantial investment required for technology deployment. Policy analysis reveals that progressive frameworks and financial incentives in select countries, like Chile and Uruguay, are fostering early adoption. Unlocking the potential of biogas-based hydrogen production in Latin America requires strategic investments, supportive policies, and enhanced regional collaboration. Strengthening these efforts can drive energy security, lower greenhouse gas emissions, and promote economic growth. Supporting regional initiatives with global sustainability objectives will position Latin America as a key player in the transition to renewable energy.

Key words: biogas-to-hydrogen conversion, economic feasibility of hydrogen, policy frameworks for bioenergy, renewable energy in Latin America, sustainable energy transition.

INTRODUCTION

The global energy landscape is undergoing a deep shift driven by the urgent need to reduce reliance on fossil fuels and mitigate the impacts of climate change. Rising concerns over resource depletion and environmental degradation have propelled the search for cleaner, more sustainable energy sources that minimize greenhouse gas (GHG) emissions and reinforce long-term energy security (Ali & Roussel, 2021). Rapid population growth and intensified industrial activities place additional pressure on conventional energy systems, underscoring the necessity of transitioning toward renewables (Soni et al., 2024). In this context, sources such as solar, wind, and bioenergy have gained momentum as viable solutions for addressing both environmental and socio-economic challenges (Hassan et al., 2024a). Within the renewable field, hydrogen stands out as a particularly promising energy carrier, with the capacity to drive deep decarbonization across transportation, industry, and power generation (Bhandari & Adhikari, 2024). However, achieving low-carbon hydrogen centres on sustainable production methods and sufficient policy support, prompting governments and international organizations to establish ambitious targets and strategic frameworks aimed at accelerating the adoption of renewable hydrogen technologies (Alam et al., 2024; Boretti & Pollet, 2024; Hassan et al., 2024b; Oluwadayomi et al., 2024).

Unlike conventional fossil fuels, hydrogen use produces minimal direct GHG emissions, offering a potential route to decrease climate impacts and enhance energy security (Evro et al., 2024). Nonetheless, hydrogen can be generated via multiple pathways, each characterized by differing cost structures, technological complexities, and environmental implications. Steam methane reforming (SMR) from natural gas remains the dominant production method but is associated with significant carbon emissions unless coupled with carbon capture and storage (CCS). Cleaner alternatives such as water electrolysis using renewable electricity or biogas reforming are attracting attention (Materazzi et al., 2024; Onwuemezie et al., 2024; Zheng et al., 2024). These options promise a smaller carbon footprint but continue to face substantial barriers in terms of cost, scalability, and infrastructure readiness. As global interest in hydrogen intensifies, stakeholders are increasingly focused on overcoming these technical and financial barriers, recognizing that effective strategies must encompass both technology-specific innovation and supportive policy frameworks (Panchenko et al., 2023; Bade et al., 2024).

Latin America is especially well-positioned to capitalize on biogas production, given its substantial agricultural, livestock, and industrial sectors that generate large volumes of organic residues (Vega et al., 2024). These residues from crop waste and animal manure to by-products of food processing can be converted into biogas via anaerobic digestion. Beyond providing a clean and flexible energy source for heating, electricity generation, and transportation, biogas offers environmental benefits by mitigating methane emissions from unmanaged organic waste (Rodrigues et al., 2025). Its use also aligns with circular economy principles, turning waste into a resource and supporting regional sustainability goals. Despite its advantages, biogas remains underutilized in much of Latin America. Contributing factors include a lack of comprehensive regulatory frameworks, insufficient policy incentives, and limited access to financial mechanisms that could encourage investment in biogas infrastructure and technology. Enhancing adoption requires not only policies that recognize the strategic value of biogas but also collaborative efforts among public and private sectors to build robust supply chains and share best practices across borders (Gallego-Schmid et al., 2024).

Steam methane reforming of biogas, which closely resembles SMR from natural gas, remains one of the most developed pathways but demands CCS to significantly reduce emissions. Autothermal reforming, combining partial oxidation with steam reforming, has shown promise by boosting thermal efficiency and hydrogen yield, although it also requires effective carbon management. Plasma reforming is an emerging technique that uses high-energy plasma to break down methane, potentially enabling decentralized applications and faster reaction rates (Jumah, 2024). Biological processes, including dark fermentation and microbial electrolysis, convert biogas into hydrogen through microbial activity, offering low-energy alternatives but still lagging in commercialization. Improving catalyst performance, integrating waste-heat recovery, and advancing carbon capture and utilization strategies could enhance the environmental profile and economic viability of these methods. However, uncertainties related to feedstock quality, process scale-up, and capital costs remain persistent obstacles (Palone et al., 2024).

Despite considerable potential, several economic and policy barriers constrain the widespread adoption of biogas-based hydrogen in Latin America. High capital expenditures restrict from the specialized infrastructure needed for purification, reforming, and carbon capture, limiting the interest of large-scale installations for investors (Swinbourn et al., 2024). In addition, many countries in the region face fragmented or inconsistent policy environments, with varying degrees of support for bioenergy initiatives (Gallego-Schmid et al., 2024). While certain nations such as Chile, Colombia, and Uruguay have presented forward-thinking hydrogen policies, others offer limited incentives or continue to subsidize fossil fuels, creating an uneven playing field for cleaner alternatives (Ferreira et al., 2025). This mixture of regulations and financial support complicates efforts to develop cohesive value chains, delaying progress in both technology deployment and market integration. Overcoming these difficulties demands government interventions that reduce project risks through tax incentives, feed-in tariffs, or targeted subsidies, as well as public-private partnerships and collaborative ventures that blend technical expertise, financial capital, and regulatory guidance (Combariza Diaz, 2024).

A coordinated regional approach is consequently crucial for unlocking Latin America’s biogas-to-hydrogen potential. While individual countries have taken steps to incorporate biogas into their energy portfolios, the lack of uniform standards, consistent incentives, and harmonized infrastructure remains a significant challenge (Luna-delRisco et al., 2024; Martins et al., 2024). A shared strategy could foster knowledge exchange, streamline permitting processes, and clarify investment pathways, ultimately accelerating the deployment of biogas-based hydrogen technologies. Regional cooperation may also facilitate the development of cross-border hydrogen transport and distribution networks, a vital component for expanding end-use applications in sectors ranging from heavy industry to mobility. By aligning regulations and leveraging collective purchasing power, Latin American nations can attract more investment and enhance their competitiveness in the global hydrogen arena (Ferreira et al., 2025).

In this study, we address the challenge of fragmented understanding regarding the technical, economic, and policy conditions for biogas-based hydrogen (BBH) production in Latin America. Although the region possesses abundant biomass resources and a growing demand for clean energy, previous research has not comprehensively integrated technological pathways, economic feasibility, and regulatory frameworks into a consolidated analysis. This gap in the current state of knowledge limits both scientific development and strategic decision-making. Therefore, the aim of this research is to systematically assess the technical potential, conversion technologies, and economic viability of BBH in Latin America, while identifying key drivers, barriers, and regional disparities. The practical objective is to provide actionable recommendations for policymakers, industry stakeholders, and investors to support the large-scale deployment of BBH technologies, contributing to the region's energy diversification and decarbonization goals. Through a scoping review of scientific literature, institutional reports, and national roadmaps, we analyse existing and emerging technologies such as steam methane reforming, autothermal reforming, plasma reforming, and biological pathways, evaluating their feasibility and cost-effectiveness in different country contexts. Additionally, we examine policy frameworks and financial instruments, highlighting areas where clearer guidelines or stronger incentives could catalyze investment. By synthesizing best practices and case studies, this study aims to fill the identified research gap and encourage the development of BBH systems as a strategic component of Latin America's sustainable energy transition and socio-economic progress.

LITTERATURE REVIEW

Overview of biogas and its role in renewable energy

Biogas is a renewable energy source derived from the anaerobic digestion of organic matter, including agricultural residues, livestock manure, wastewater sludge, and municipal solid waste. This process produces a methane-rich gas that can be utilized for electricity generation, heating, and as a feedstock for advanced biofuels, including hydrogen (Luna-delRisco et al., 2011). Compared to fossil fuels, biogas offers significant environmental benefits by reducing methane emissions from decomposing organic waste, improving waste management, and promoting circular economy principles (Tjutju et al., 2024). A study conducted by Tjutju et al. (2024) have shown that biogas production not only enhances energy security but also provides economic opportunities for rural communities, particularly in regions with strong agricultural and livestock industries. In general, the integration of biogas into renewable energy systems has been widely explored, with successful implementations in Europe and North America. Fig. 1 illustrates the role of biogas across various industries, highlighting high-impact and value-added areas where these systems have been implemented. However, Latin America's biogas potential remains largely unexploited due to infrastructure limitations, policy fragmentation, and technological barriers (Gallego-Schmid et al., 2024). Recent research highlights that, despite the availability of organic feedstocks, biogas adoption in Latin America faces financial and institutional challenges that must be addressed to unlock its full potential (Luna-delRisco et al., 2025). Addressing these issues requires a combination of technological advancements, policy incentives, and investment in infrastructure to facilitate the large-scale deployment of biogas-based energy systems.

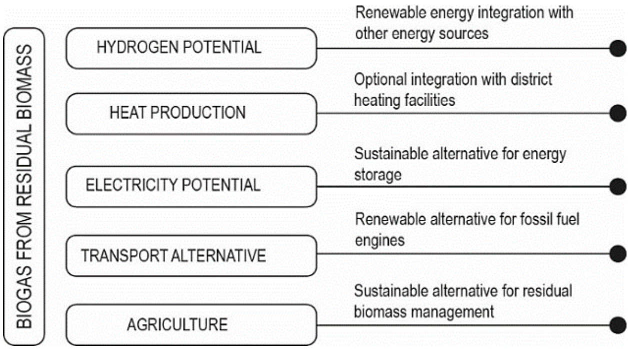

Figure 1. Role of biogas in a renewable energy system.

Hydrogen production pathways from biogas

The conversion of biogas into hydrogen involves several technological pathways, each with distinct efficiencies, costs, and environmental impacts (Fig. 2). The most widely adopted method is steam methane reforming (SMR), which reacts to methane in biogas with high-temperature steam to produce hydrogen and carbon dioxide. While SMR is commercially mature, it requires carbon capture and storage (CCS) to minimize greenhouse gas (GHG) emissions (Jeje et al., 2024). Autothermal reforming (ATR) integrates partial oxidation and SMR, improving thermal efficiency while reducing energy input requirements.

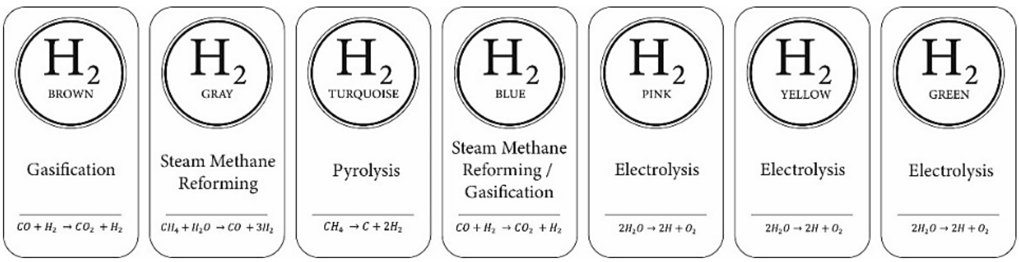

Figure 2. Alternative hydrogen production pathways.

Plasma reforming is an emerging technology that employs high-energy plasma to break down methane, offering rapid reaction rates and decentralized applications. Additionally, biological hydrogen production, such as dark fermentation and microbial electrolysis cells, provides alternative pathways that utilize microbial activity to generate hydrogen directly from biogas (Alhamed et al., 2024). These biological methods offer lower energy consumption but remain at early research stages due to scalability challenges. Studies suggest that optimizing these technologies through advanced catalysts, process automation, and hybrid conversion systems could enhance biogas-to-hydrogen efficiency (Kumar & Kumar, 2024). However, economic constraints and infrastructure gaps remain key barriers.

Technological advances in Biogas-to-Hydrogen (B2H) conversion

Recent advancements in catalysis, purification techniques, and carbon management strategies have significantly improved the efficiency of B2H conversion. Nanostructured catalysts have shown enhanced performance in reforming processes by increasing reaction rates and reducing energy input requirements (Saeed et al., 2024). In purification, membrane separation technologies, such as palladium-based membranes, have demonstrated high selectivity for hydrogen extraction, reducing impurities like carbon monoxide and residual methane (Yang et al., 2025). Additionally, pressure swing adsorption (PSA) systems have been optimized to improve hydrogen purity while minimizing energy losses (Shabbani et al., 2024). In terms of carbon management, integrated carbon capture utilization and storage (CCUS) is gaining interest in mitigating emissions associated with methane reforming. A study conducted by Cho et al. (2024) have also explored hybrid systems, combining SMR with renewable electrolysis, to enhance hydrogen yields while reducing reliance on fossil energy alternatives. Moreover, advancements in biological conversion techniques, including genetically engineered microorganisms for microbial electrolysis, show promise in improving hydrogen productivity at lower temperatures (Jain et al., 2022). While these technological innovations contribute to increased efficiency, their commercial viability remains a challenge due to high capital costs and infrastructure requirements.

Economic feasibility of Biogas-Based Hydrogen (BBH)

The economic viability of BBH production depends on multiple factors, including feedstock availability, process efficiency, capital investment, and market demand. Studies indicate that biogas production costs vary significantly across regions, with lower costs in countries with abundant organic waste resources (Rodrigues et al., 2025). However, hydrogen conversion technologies remain capital-intensive, particularly for advanced purification systems and carbon capture integration. Comparative cost assessments reveal that biogas-to-hydrogen pathways are currently more expensive than fossil-based hydrogen production, but with economies of scale and policy incentives, costs could decline over time (Emetere et al., 2024). Financial models suggest that government subsidies, tax credits, and carbon pricing mechanisms could improve the economic feasibility of biogas-derived hydrogen. Additionally, public-private partnerships and regional investment funds have been identified as key enablers for accelerating commercial deployment. Studies emphasize that market competitiveness can be enhanced through value chain optimization, including the development of integrated biorefineries that maximize resource utilization (Jaradat et al., 2024). Despite these opportunities, economic barriers such as high initial investments, limited financing mechanisms, and uncertain policy frameworks continue to slow down large-scale technology positioning (Emetere et al., 2024). Addressing these challenges requires targeted financial incentives and regulatory support to create a favorable investment environment for BBH technologies.

Policy frameworks and regulatory challenges

A well-structured policy framework is crucial for the successful deployment of B2H technologies. Currently, policy support varies significantly across Latin American countries, with some nations implementing hydrogen roadmaps while others lack clear regulations for biogas utilization. A comparative analysis reveals that Chile, Colombia

Uruguay have introduced incentive programs for green hydrogen, including tax exemptions and funding for pilot projects (Gomes et al., 2024). However, many countries in the region still prioritize fossil fuel subsidies, making renewable hydrogen less competitive. Studies highlight that regulatory uncertainty, lack of standardization, and fragmented institutional frameworks create barriers for investors and project developers (Carlson & Trencher, 2024). Furthermore, permitting processes and grid connection regulations often delay the deployment of B2H infrastructure. Data reported for international experiences suggests that long-term policy commitments, carbon pricing mechanisms, and renewable energy mandates can significantly boost investor confidence (Bade & Tomomewo, 2024). Research also underscores the importance of harmonized regional policies, allowing for cross-border collaboration and knowledge exchange. Strengthening these policy frameworks will be essential to accelerate the development of a competitive BBH sector in Latin America.

Environmental and sustainability considerations

BBH offers significant environmental benefits compared to fossil-based hydrogen (FBH) production. Life-cycle assessments indicate that biogas-derived hydrogen (BDH) can achieve carbon neutrality when integrated with carbon capture technologies. Additionally, biogas mitigates methane emissions, reducing its environmental impact. However, sustainability challenges remain, including land use competition, water consumption, and waste management complexities. Research highlights that circular economy approaches, such as nutrient recovery from digestate, can enhance the sustainability of biogas projects (Le et al., 2024). Integrating these sustainability measures will be essential to ensuring the long-term viability of BBH.

METHOD

This study considers a comprehensive research approach to assess the technical and economic feasibility of biogas-based hydrogen production in Latin America. The methodology integrates quantitative and qualitative analyses, incorporating data from scientific literature, government reports, industrial case studies, and stakeholder perspectives. A systematic framework was designed to evaluate biomass availability, conversion technologies, economic viability, and policy frameworks relevant to the region. The research follows a structured methodology comprising the following key components:

Data collection and sources

A systematic review of scientific literature, policy documents, and technical reports was conducted to obtain relevant data on BBH production. A scoping review, following PRISMA-ScR guidelines (Tricco et al., 2018), was conducted to comprehensively map and synthesize the available evidence on biogas-based hydrogen (BBH) production in Latin America. The review included scientific literature, policy documents, technical reports, and economic datasets published in the last five years (2019–2024). Data sources included peer-reviewed publications from indexed scientific journals to assess technological advancements, efficiency data, and innovation trends, policy documents and national hydrogen roadmaps from Latin American governments and international organizations (e.g., IRENA, IDB) to understand regulatory frameworks, and economic data extracted from energy market reports, investment outlooks, and international funding databases.

The literature search strategy focused on data consultation using Scopus, Web of Science, and Google Scholar, employing key terms such as ‘biogas hydrogen production’, ‘biogas reforming’, ‘biohydrogen Latin America’, ‘hydrogen policy Latin America’, and ‘BBH techno-economic analysis’. Additionally, grey literature was incorporated by reviewing institutional repositories, governmental platforms, and international reports.

The data gathering method also considered the inclusion and exclusion of different criteria. Publications focused on biogas utilization, hydrogen production pathways, economic feasibility, and policy frameworks relevant to Latin America, as well as studies published in English and Spanish were considered as inclusion criteria, while studies focused exclusively on other hydrogen production pathways without reference to biogas, and regions outside Latin America unless presenting globally relevant technological benchmarking were excluded from this study.

The selected publications were screened for relevance based on titles and abstracts, followed by full-text reading. The sources were then categorized by topics (technical, economic, policy), geographical relevance (country-specific or regional), and publication type (peer-reviewed, report, roadmap).

A descriptive-analytical approach was applied, summarizing key technological parameters (i.e. efficiency, yields), economic indicators (i.e. investment costs), and policy instruments. The data were then cross-referenced with global benchmarks to identify gaps and opportunities.

Data validation was performed through cross-referencing multiple sources and prioritizing publications from highly ranked journals or institutional reports.

Technological evaluation

The technical analysis of biogas-based hydrogen production in Latin America was conducted using a multidisciplinary approach, integrating biomass resource assessment, conversion technology evaluation, hydrogen purification analysis, and global benchmarking.

Data from national agricultural agencies, industry reports, and scientific literature were analyzed to determine the availability and distribution of biomass. A comparative analysis of hydrogen production pathways was conducted. The study also approaches hydrogen purification methods and carbon capture strategies, emphasizing their role in enhancing hydrogen purity and sustainability.

Economic feasibility analysis

A brief approach to the cost-benefit analysis was conducted to assess the financial viability of biogas-based hydrogen production. The economic evaluation considers: i) capital expenditures (CAPEX) and operational expenditures (OPEX) for infrastructure, technology deployment, and feedstock processing, ii) levelized cost of hydrogen (LCOH) to compare production costs with conventional and renewable hydrogen sources, and iii) financial incentive scenarios, including government subsidies, carbon pricing mechanisms, and tax incentives.

Policy and regulatory framework analysis

An overview of existing policies, regulations, and government initiatives was conducted to assess their role in promoting or delaying biogas-to-hydrogen adoption. The analysis included a brief comparison of some national hydrogen strategies across Latin America, focusing on policy incentives for bioenergy-based hydrogen. The study also reviewed some regulatory barriers, such as lack of standardization, grid integration challenges, and permitting processes.

Definition of analysis timeframes

This study defines three analytical timeframes: short-term (0–5 years), mid-term (6–10 years), and long-term (> 10 years) to facilitate the assessment of policy gaps, regulatory barriers, and technological deployment challenges. The selection of these intervals was based on internationally recognized strategic planning frameworks and hydrogen development roadmaps (IRENA, 2022; IEA, 2024; European Hydrogen Backbone Initiative, 2021). The short-term period focuses on immediate regulatory actions, the initial deployment of technologies, and the investment challenges that arise in the early stages. The mid-term covers the phase where infrastructure expands, markets stabilize, and institutional frameworks become more robust. Finally, the long-term perspective looks at how systems integrate on a larger scale, how countries collaborate across borders, and how emerging technologies evolve and mature. These timeframes follow well-established models of how technologies progress toward readiness (Mankins, 2009) and how innovations spread and are adopted (Rogers, 2003). They also reflect the typical legislative, financial, and industrial cycles observed in major energy transitions. Using this structure helps organize and prioritize the key challenges and opportunities for developing BBH in Latin America.

Limitations of the study

While this research provides an evaluation of biogas-based hydrogen production, the authors state that certain limitations exist. The limitations found in this study are data availability, technology cost fluctuations, and policy variability. Despite these limitations, the study offers ground for decision-making and identifies key areas for future research and policy interventions.

RESULTS AND DISCUSSION

Technical analysis

The technical analysis of biogas-based hydrogen production in Latin America focuses on the availability of biomass feedstocks, conversion technologies, and key performance indicators for hydrogen yield and efficiency. The findings provide insights into the feasibility of integrating biogas-to-hydrogen conversion technologies into the region's energy landscape.

Biomass resource potential for biogas production. The assessment of organic feedstocks for biogas production across Latin America reveals that agricultural residues, livestock manure, and municipal solid waste are the most abundant sources. Brazil, Argentina, Colombia, and Mexico stand out as high-potential regions due to their extensive agricultural and livestock industries. Sugarcane bagasse, coffee husks, and palm oil residues present substantial opportunities for biogas generation. Data from national agricultural agencies indicate that millions of tons of organic waste per year remain underutilized, highlighting a significant untapped potential for bioenergy applications (Fig. 3).

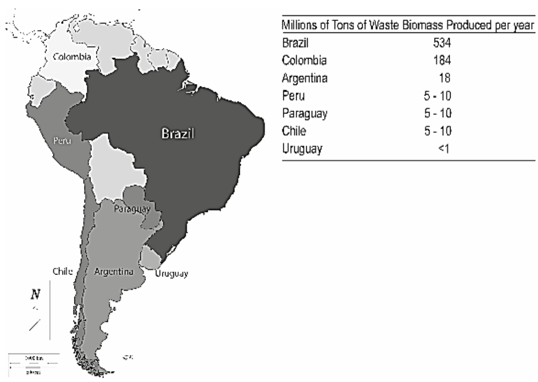

Figure 3. Volume of waste biomass produced per year in various countries of South America.
Source: adapted from (Sampaolesi et al., 2023).

Despite the abundance of feedstocks, logistical and infrastructural barriers affect biogas availability. In some regions, poor waste collection systems, lack of centralized biogas plants, and limited access to processing technologies constrain large-scale production. Additionally, variability in feedstock composition influences methane content, impacting hydrogen yield in conversion processes (Mignogna et al., 2024). These findings emphasize the need for improved waste management systems, efficient feedstock preprocessing, and decentralized biogas plants to enhance resource utilization for hydrogen production.

Performance of Biogas-to-Hydrogen (B2H) conversion technologies. The comparative analysis of hydrogen production pathways from biogas highlights differences in efficiency, cost-effectiveness, and technological readiness levels (TRLs). Steam methane reforming (SMR) remains the most widely used method due to its high hydrogen yield (approx. 70–80%) and commercial maturity. However, its carbon dioxide emissions require integration with carbon capture and storage (CCS) to align with sustainability goals. In contrast, autothermal reforming (ATR) offers improved thermal efficiency by combining partial oxidation and steam reforming, but its operational complexity presents a challenge for large-scale adoption (Kumar & Kumar, 2024; Materazzi et al., 2024).

Emerging technologies such as plasma reforming and biological hydrogen production have demonstrated promising results in laboratory-scale experiments, yet they remain in early development stages. Plasma reforming achieves rapid methane conversion with minimal energy input, but infrastructure costs are high. Microbial electrolysis cells (MECs) and dark fermentation techniques leverage biological pathways to produce hydrogen at lower temperatures but exhibit lower yields and scalability constraints (Ahmad et al., 2024; Singh et al., 2024). These findings suggest that while conventional thermochemical pathways are currently the most viable for large-scale applications, ongoing research and innovation in catalysis, reactor design, and process optimization are essential to improve the efficiency and sustainability of biogas-to-hydrogen conversion.

Hydrogen purification and carbon management strategies. Hydrogen purification is critical to achieving fuel cell-grade hydrogen from biogas-derived sources. The study finds that membrane separation technologies, pressure swing adsorption (PSA), and cryogenic distillation are the most effective purification techniques (Kazmi et al., 2024; Król et al., 2024; Yang et al., 2025). Palladium-based membranes provide high selectivity but remain expensive, whereas PSA systems balance cost and efficiency, making them suitable for commercial applications. Recent advancements in metal-organic frameworks (MOFs) and hybrid separation techniques show potential for improving gas separation efficiency and reducing energy consumption.

In parallel, carbon capture and utilization (CCU) strategies are necessary to mitigate emissions from methane reforming processes. Absorption-based CO_2 capture using amine solvents remains the dominant approach, but novel techniques such as mineralization and bio-based CO_2 conversion offer sustainable alternatives. The integration of biogas upgrading technologies with carbon capture systems can enhance overall sustainability by producing both high-purity hydrogen and renewable biomethane.

Energy efficiency and system integration challenges. The overall energy efficiency of B2H systems depends on process integration, heat recovery mechanisms, and operational conditions. Energy efficiency assessments indicate that SMR with CCS achieves an efficiency range of 50–60%, while ATR reaches slightly higher efficiencies due to internal heat utilization. Plasma reforming and biological hydrogen production pathways exhibit lower efficiencies but offer potential advantages in decentralized applications (Zainal et al., 2024).

A key challenge identified is the integration of B2H systems into the existing energy infrastructure. The lack of dedicated hydrogen transport networks, refueling stations, and grid connections in Latin America presents barriers to widespread adoption. Hybrid biorefinery models, where hydrogen production is combined with biomethane upgrading and biofertilizer recovery, could enhance system efficiency and economic viability. A study conducted by Jaradat et al. (2024) suggests that sector coupling strategies, linking hydrogen with renewable power, industrial applications, and mobility sectors, could accelerate market development.

Comparative analysis with global benchmarks. A comparative analysis with leading B2H initiatives in Europe, North America, and Asia reveals key lessons for Latin America. Germany's hydrogen strategy prioritizes renewable gas integration and sector- wide collaboration, serving as a model for policy-driven deployment. Japan's investment in hydrogen infrastructure and fuel cell applications highlights the role of government funding in accelerating technology adoption. Meanwhile, Denmark's bioenergy-focused policies showcase the economic benefits of linking biogas production with hydrogen and biomethane markets (Fig. 4).

Figure 4. Green hydrogen market trends by region (2025–2030).

Source: Adapted from (Green Hydrogen Market Size, Share & Growth Report, 2030).

Latin America has the advantage of abundant biomass resources and growing energy demand, but it lags in infrastructure, policy incentives, and research investment. Bridging this gap requires greater government commitment, regional cooperation, and industry-driven innovation to replicate successful international models while addressing region-specific challenges.

Economic feasibility analysis

The economic viability of BBH production in Latin America depends on multiple cost-related, market, and policy factors that influence its competitiveness compared to other hydrogen sources. The findings in this section provide a comprehensive evaluation of capital and operational costs, financial incentives, market trends, and investment challenges for technology adoption.

Capital and operational costs of B2H production. The economic assessment reveals that capital expenditures (CAPEX) and operational expenditures (OPEX) for BBH production remain higher than conventional hydrogen production methods, particularly steam methane reforming (SMR) from fossil fuels (Yagüe et al., 2024; Cormos, 2025). The CAPEX of B2H systems is influenced by feedstock processing, anaerobic digestion infrastructure, gas upgrading technologies, and hydrogen purification units. Cost estimates indicate that the installation of a medium-scale biogas plant capable of hydrogen production requires an initial investment ranging between $5–15 million, depending on technology choice and plant capacity. The most expensive components are gas cleaning and reforming units, as they require advanced materials and catalytic systems to ensure high hydrogen yields (Yagüe et al., 2024).

On the other hand, OPEX is affected by feedstock costs, maintenance, and energy requirements for reforming processes. Unlike fossil-based hydrogen production, biogas-based systems require continuous biomass supply chains, which introduce logistical challenges and price variability. A study conducted by Loh et al. (2024) show that OPEX for biogas-based hydrogen plants can be reduced through economies of scale, particularly if co-products such as biomethane, electricity, and biofertilizers are integrated into the business model. These findings suggest that cost reduction strategies must focus on optimizing feedstock supply chains, improving plant efficiency, and adopting modular designs for smaller-scale distributed production.

Levelized cost of hydrogen from biogas. The Levelized Cost of Hydrogen (LCOH) is a critical economic indicator for assessing the feasibility of biogas-derived hydrogen compared to other production methods. In Latin America, LCOH estimates for biogas-based hydrogen range between $3.50 and $7.00 per kilogram (kg), depending on factors such as feedstock availability, technology selection, and production scale (IRENA & IDOS, 2024). This cost is higher than fossil-based hydrogen (gray hydrogen), which averages $1.50–$2.50 kg, but competitive with green hydrogen from electrolysis, which ranges from $4.00–$7.50 kg.

The economic analysis identified 3 key cost drivers for biogas-to-hydrogen LCOH. The variables are: i) feedstock costs, in which regions with abundant organic waste can achieve lower LCOH due to minimal raw material expenses, ii) plant efficiency leads to high methane conversion rates in steam methane reforming (SMR) and autothermal reforming (ATR) improve overall hydrogen output, reducing costs, and iii) existing carbon pricing incentives in countries where carbon credits incentives exist, biogas-based hydrogen can achieve cost parity with fossil-derived alternatives (Loh et al., 2024). These drivers suggest that cost reductions through process optimization, increased scale, and financial incentives are possible.

Financial incentives and government support. Financial incentives play a crucial role in making biogas-based hydrogen competitive in the energy market. Currently, Latin America lacks a standardized incentive framework for hydrogen production from biogas, leading to investment uncertainty and slower adoption rates. However, some countries have introduced policies that support bioenergy and hydrogen production, which could provide indirect benefits to biogas-based systems (Tunn et al., 2024).

This study approaches a few key financial mechanisms that influence project feasibility. First, subsidies for renewable hydrogen in countries like Chile and Uruguay have initiated hydrogen investment funds, although most target electrolysis-based hydrogen. Tax incentives for bioenergy projects in Brazil and Argentina provide tax reductions and investment credits for biogas plants, which could extend to hydrogen production. Carbon pricing schemes for countries implementing carbon taxes or emission reduction programs (e.g., Colombia) could create an economic advantage for low-emission hydrogen pathways. At last, international funding and grants awarded for Latin American projects from organizations such as the Inter-American Development Bank (IDB) and the Global Environment Facility (GEF), supporting renewable energy deployment (Tunn et al., 2024; Undurraga et al., 2024).

Despite these efforts, biogas-based hydrogen lacks specific financial policies that directly support its expansion. Establishing targeted subsidies, preferential financing, and carbon credit incentives could significantly reduce investment risks and improve economic feasibility.

Market competitiveness and commercial viability. The commercial viability of biogas-derived hydrogen depends on its ability to compete with other hydrogen production methods in the energy and industrial sectors. At present, gray hydrogen (from natural gas) dominates industrial applications due to lower costs and well-established supply chains. However, carbon-intensive hydrogen is becoming less favorable due to stricter decarbonization policies worldwide (Saha et al., 2024).

Based on the context of this study, Latin America has potential market opportunities for biogas-based hydrogen supported on the following axis: i) decarbonizing heavy industries, which focuses on sectors such as steel, cement, and chemical production that require sustainable hydrogen alternatives, providing an immediate demand for renewable hydrogen, ii) hydrogen for mobility solutions in which some countries, including Chile, Colombia and Brazil, have introduced pilot projects for hydrogen-powered vehicles such cars, buses and trucks, presenting a future market for biogas-derived hydrogen, and iii) grid integration and energy storage from hydrogen produced from biogas; this could be used to stabilize energy grids by storing surplus renewable energy and providing backup power (Gomes et al., 2024).

In the study conducted by Jaradat et al. (2024), the authors presented results in which market competitiveness was improved due to biogas-based hydrogen integration into national hydrogen roadmaps, ensuring long-term demand, pricing stability, and infrastructure development.

Investment challenges and risk analysis. The economic risks associated with biogas-to-hydrogen projects are related to factors such as high capital costs, regulatory uncertainty, and limited market demand. Investors and private sector stakeholders require clear financial incentives, stable policy frameworks, and access to financing mechanisms before committing to large-scale projects.

Jaradat et al. (2024) have found challenges associated to: i) lack of standardized regulations, because of the absence of clear hydrogen certification frameworks creates market uncertainty, discouraging investors, ii) limited infrastructure for hydrogen storage and transport networks. Private initiatives and government efforts are still underdeveloped, increasing logistical costs, and iii) volatile feedstock supply chains due to seasonal variations in agricultural and livestock. This volatility of available waste can affect biogas production consistency.

The findings suggest that risk mitigation strategies should focus on regional cooperation, government-backed guarantees, and Public-Private Partnerships (PPPs) to ensure long-term investment security.

Policy and regulatory analysis

The development of biogas-based hydrogen production in Latin America deeply depended on policy frameworks, regulatory incentives, and government support. While some countries have introduced hydrogen roadmaps and bioenergy policies, a lack of regulatory harmonization, investment security, and infrastructure planning continues to slow technology adoption and exploitation. The evaluation of the current policy landscape, existing barriers, and potential regulatory improvements to accelerate the adoption of biogas-based hydrogen in the region was evaluated.

National hydrogen strategies and their impact on Biogas-Based Hydrogen. This study approaches Latin American countries that have formulated hydrogen strategies to align with global decarbonization goals, in which most policies prioritize electrolysis-based hydrogen over bioenergy pathways. Chile, Uruguay, Brazil, and Colombia have developed hydrogen roadmaps that outline investment plans, market development goals, and pilot project funding (IRENA & IDOS, 2024). However, biogas-based hydrogen is rarely specified as a key component of these strategies, despite the region's large biomass resources and existing bioenergy infrastructure. Table 1 provides a comparison of selected national hydrogen strategies and their challenges regarding biogas-based hydrogen production.

Table 1. Overview of selected national hydrogen policies and challenges for Biogas-Based Hydrogen in Latin America

Country	Policy Status	Challenges
Chile	One of the most advanced hydrogen policies with subsidies and investment funds for green hydrogen.	Focuses primarily on solar-powered electrolysis with minimal emphasis on biogas utilization.
Uruguay	Integrates bioenergy within its renewable energy transition.	Lacks specific policies to incentivize hydrogen production from biogas.
Brazil	Strong biofuels sector with bioenergy incentives that indirectly support biogas projects.	Direct policy mechanisms for hydrogen production remain underdeveloped.
Colombia	Hydrogen roadmap acknowledges biohydrogen as a potential pathway.	Financial and technical incentives for biohydrogen remain unclear.

Source: own elaboration.

Policy gaps and regulatory barriers. Despite growing interest in renewable hydrogen, Latin America faces significant policy gaps and regulatory challenges that delay the development of biogas-based hydrogen projects. In Table 2, the authors present a table that categorizes the urgency of policy gaps and regulatory barriers based on their impact on short-term, middle-term, and long-term projects.

Table 2. Outlook of policy gaps and regulatory barriers in Latin America

Policy Gaps and Regulatory Barriers	Short-Term (0–5 years)	Middle-Term (6–10 years)	Long-Term (>10 years)
Lack of standardized hydrogen regulations	**Critical**	Moderately Critical	Not Critical
Limited financial incentives for bioenergy-based hydrogen	**Critical**	**Critical**	Moderately Critical
Complex permitting and approval processes	**Critical**	Moderately Critical	Moderately Critical
Absence of carbon pricing mechanisms	Moderately Critical	**Critical**	**Critical**
Weak integration of biogas into national hydrogen strategies	**Critical**	**Critical**	Moderately Critical
Limited infrastructure for hydrogen storage and transport	**Critical**	**Critical**	**Critical**
Fragmented regional policies and lack of coordination	Moderately Critical	**Critical**	**Critical**
Slow development of public-private partnerships (PPPs)	Moderately Critical	Moderately Critical	Moderately Critical
Unclear land-use policies for biogas facilities	**Critical**	Moderately Critical	Not Critical
Lack of research and development (R&D) funding for biogas-based hydrogen	Moderately Critical	**Critical**	**Critical**

Source: own elaboration.

The table highlights key policy gaps and regulatory barriers impacting biogas-based hydrogen production in Latin America across short-term (0–5 years), middle-term (6–10 years), and long-term (> 10 years) timeframes. In the short term, critical challenges include the lack of standardized hydrogen regulations, limited financial incentives, complex permitting processes, weak policy integration of biogas, and insufficient infrastructure for hydrogen storage and transport. These barriers create investment uncertainty and delay project scalability, requiring immediate policy reforms and financial incentives. In the middle term, challenges such as the absence of carbon pricing mechanisms, fragmented regional policies, and inadequate research and development (R&D) funding become more pronounced, requiring coordinated governmental action to establish market-driven regulations, harmonize policies, and foster technology advancements. In the long term, sustaining investment in infrastructure and innovation will be essential to ensuring the competitiveness of biogas-based hydrogen. Although regulatory improvements and technological advancements may mitigate some short-term and middle-term issues, long-term challenges, including infrastructure expansion and policy stability, will require continuous managing. Addressing these policy gaps through government commitment, international collaboration, and private-sector engagement will be crucial to unlocking the full potential of biogas-based hydrogen, positioning Latin America as a key player in the global hydrogen economy.

The role of carbon pricing and emissions regulations. Carbon pricing mechanisms are important in determining the economic competitiveness of biogas-based hydrogen. Countries implementing carbon taxes or emissions trading systems (ETS) create stronger market incentives for low-carbon hydrogen (Ueckerdt et al., 2024; J. Yang et al., 2024). However, in Latin America, carbon pricing remains underdeveloped and inconsistently applied. Colombia has a carbon tax primarily targeting fossil fuel industries, offering limited incentives for biohydrogen production. Argentina and Brazil have regional emissions reduction programs, yet hydrogen-related credits are not widely available. Mexico previously explored carbon trading systems, but policy reversals have slowed progress. A regional carbon pricing mechanism, combined with hydrogen-specific emission reduction credits, could enhance the economic feasibility of biogas-to-hydrogen projects while promoting low-carbon energy adoption (Missbach et al., 2024).

Latin America possesses abundant renewable energy resources, positioning it to become a major producer of low-cost, low-emission hydrogen, particularly in countries like Argentina, Brazil, Colombia, and Chile. Despite this potential, the region's bioenergy capabilities have been only partially developed, with significant opportunities remaining untapped. Implementing comprehensive carbon pricing strategies and fostering regional cooperation could unlock these opportunities, advancing both economic and environmental objectives.

However, the economic viability of biogas-based hydrogen production in Latin America faces significant challenges. High capital costs associated with biogas plant construction and operation, coupled with limited access to financing, impede project development. Additionally, the absence of standardized regulations and incentives for biohydrogen creates uncertainty for investors. Technological challenges, such as the need for efficient biomass collection and processing, further complicate the technology adoption panorama. Addressing these issues requires coordinated policy frameworks, investment in research and development, and the establishment of financial mechanisms to support biogas-based hydrogen initiatives (Rodríguez-Fontalvo et al., 2024).

Opportunities and Challenges

The potential for biogas-based hydrogen production in Latin America is driven by abundant biomass resources, growing hydrogen markets, environmental benefits, and socio-economic advantages. Countries like Brazil, Argentina, Colombia, and Mexico possess significant agricultural and livestock industries, providing a sustainable supply of organic waste for biogas production. These feedstocks offer a low-cost alternative to fossil fuels, reducing dependency on imported energy sources. Additionally, Chile and Brazil are emerging as hydrogen market leaders, investing in infrastructure and national strategies that could integrate biogas-based hydrogen to strengthen energy security and economic growth.

From an environmental perspective, biogas-derived hydrogen significantly reduces methane emissions, aligning with climate policies and global decarbonization efforts. When coupled with carbon capture and utilization (CCU) technologies, biohydrogen can even achieve low emissions, making it attractive for industrial applications seeking low-carbon energy alternatives.

Beyond economic and environmental benefits, biogas-based hydrogen has strong socio-economic potential, particularly for rural development. Countries with strong agricultural sectors can create jobs in feedstock collection, biogas plant operation, and hydrogen distribution, while decentralized energy systems can increase energy access in remote areas.

Table 3. Analysis and comparison of opportunities for biogas-based hydrogen development in Latin America

Country	Biomass availability	Hydrogen market integration	Environmental impact and decarbonization	Socio-economic potential	Challenges and limitations
Brazil	**High** Large agricultural and livestock waste (sugarcane bagasse, soy residues, manure)	**Strong** Already investing in green hydrogen; potential for biohydrogen inclusion	**High** Existing biogas infrastructure could reduce methane emissions significantly	**Strong** Biogas sector already supports rural employment; potential to expand hydrogen workforce	**Policy Gaps** Hydrogen roadmap prioritizes electrolysis; limited direct incentives for biohydrogen
Argentina	**High** Extensive livestock and agro-industrial waste (corn, wheat, cattle manure)	**Moderate** Emerging interest in hydrogen, but biohydrogen not yet prioritized	**Moderate** Biogas projects exist, but few large-scale hydrogen applications	**Moderate** Potential for rural job creation, but lack of investment in hydrogen production	**Economic Constraints** Limited funding mechanisms for biogas-to-hydrogen projects
Colombia	**Moderate** Strong agricultural output (coffee, palm oil, livestock waste), but uneven waste collection	**Moderate** Hydrogen strategy mentions biohydrogen, but lacks detailed implementation plans	**Moderate** Some biogas projects, but weak integration into hydrogen sector	**Moderate** Potential for decentralized rural energy access and economic growth	**Regulatory Uncertainty** Biohydrogen incentives remain unclear, slowing investment
Mexico	**High** Diverse biomass sources (corn, sugarcane, livestock waste, municipal solid waste)	**Weak** Limited hydrogen policy development; no strong biohydrogen incentives	**Moderate** Potential for emissions reduction, but few government-backed projects	**Moderate** Could create rural jobs, but requires policy support.	**Infrastructure Limitations** Lacks hydrogen transport and storage capacity
Chile	**Low to Moderate** Limited biomass, but potential for municipal waste utilization	**Very Strong** Regional leader in green hydrogen, strong government backing	**High** Hydrogen roadmap prioritizes decarbonization; potential CCU applications	**Low** Rural biohydrogen projects unlikely due to lower biomass availability	**Feedstock Constraints** Limited agricultural waste may restrict large-scale biogas-to-hydrogen projects

Source: own elaboration.

The comparative analysis presented in Table 3, highlights Brazil and Argentina as the most viable candidates for biogas-based hydrogen production due to their abundant biomass resources and strong agricultural sectors, however Argentina's policy and investment barriers may delay progress. Colombia and Mexico possess moderate potential, but weak regulatory frameworks and infrastructure constraints limit their ability to scale biohydrogen projects effectively. While Chile leads in hydrogen market development, its limited biomass availability reinforces its reliance on electrolysis-based hydrogen, restricting the role of biogas-derived pathways. Despite the region's vast bioenergy potential, the predominant policy fragmentation, infrastructure deficits, and economic challenges create significant barriers to deployment, indicating that without stronger government incentives, clearer regulatory frameworks, and regional cooperation, biogas-to-hydrogen production will struggle to compete with other hydrogen pathways in Latin America's clean energy transition (IRENA & IDOS, 2024).

Challenges Facing Biogas-Based Hydrogen Deployment. The economic, infrastructural, policy, and technological barriers outlined in the analysis present significant barriers to the widespread deployment of biogas-based hydrogen in Latin America. A lack of hydrogen infrastructure further constrains deployment, as Latin America lacks the necessary transport, storage, and distribution networks for biogas-based hydrogen. While natural gas systems are well established, the hydrogen economy is still in its early stages, requiring substantial investment in compression, liquefaction, and pipeline development.

In addition to economic and infrastructure challenges, policy and regulatory uncertainty remains a major deterrent for private sector participation. Most hydrogen roadmaps in Latin America focus on electrolysis-based hydrogen, while biogas-derived hydrogen receives little policy support. Furthermore, complex permitting processes and fragmented regulations discourage investment in emerging biohydrogen projects.

From a technological perspective, there are limitations that present additional constraints. While commercially available conversion methods such as SMR and ATR are viable, they remain energy-intensive, increasing production costs. Emerging technologies like microbial electrolysis cells and plasma reforming could provide more efficient and cost-effective solutions, but they are still in early research stages. Addressing these technological inefficiencies will require sustained investment in R&D.

Despite these challenges, Latin America's vast biomass resources, growing renewable energy demand, and potential for emissions reductions create strong opportunities for biogas-based hydrogen if governments and industries implement targeted financial incentives, infrastructure investments, and regulatory reforms. Table 4 presents a regional analysis of barriers found in studied Latin American countries.

The comparative analysis presented in Table 4 highlights that Colombia and Mexico face severe infrastructure and regulatory gaps, requiring stronger financial incentives and policy reforms to facilitate biohydrogen development. While Chile leads in green hydrogen policies, its limited biomass availability constrains biogas-based hydrogen potential, necessitating alternative strategies for biohydrogen integration. The critical challenge across all countries lies in technological advancements that requires governments to improving reforming efficiency, purification processes, and cost reductions in biogas upgrading to succeed commercial viability. Although these challenges, opportunities exist if governments implement strategic policies, strengthen financial mechanisms, and invest in research and infrastructure. Latin American nations with strong agricultural sectors must prioritize biohydrogen within hydrogen strategies, while Colombia and Mexico need targeted regulatory improvements to attract investments. Without coordinated actions, technology improvements, and policy support, biogas-based hydrogen will have difficulties to compete with electrolysis-based hydrogen and fossil-based alternatives in the region's clean energy transition.

Table 4. Comparative analysis of economic, infrastructural, and policy barriers in Latin America

Country	Economic challenges (CAPEX & OPEX)	Infrastructure gaps	Policy & regulatory uncertainty	Technological barriers
Brazil	**High** Significant investment needed for biogas digesters and reforming technologies. LCOH remains uncompetitive	**Moderate** Existing biogas infrastructure could support hydrogen but requires upgrades	**Moderate** Biohydrogen is not a priority in hydrogen roadmap, but biofuels sector could drive integration	**Moderate** SMR is dominant, but advancements in plasma reforming could enhance efficiency
Argentina	**High** Limited financing for hydrogen projects makes CAPEX-intensive biogas plants difficult to scale	**High** Weak hydrogen transport and storage infrastructure	**High** No clear national hydrogen strategy; fragmented regulatory framework	**Moderate** Need for R&D investments to improve efficiency
Colombia	**Moderate** Biogas sector is growing, but hydrogen conversion remains costly without subsidies	**High** Lack of hydrogen storage and distribution networks	**High** Limited policy support for biogas-based hydrogen; regulatory uncertainty	**High** Need for process optimization and improved methane reforming efficiency
Mexico	**High** High LCOH due to expensive reforming and purification technologies	**High** Poor hydrogen transport infrastructure; no large-scale biogas-hydrogen integration	**High** Lack of clear regulations and financial incentives for biogas-based hydrogen	**Moderate** Potential for microbial electrolysis but still in early research phase
Chile	**Moderate** High energy prices affect biogas-to-hydrogen economics, but investment climate is strong	**Moderate** Hydrogen roadmap prioritizes electrolysis, with limited biogas integration	**Low** Clear hydrogen policies exist, but biohydrogen receives minimal direct incentives	**High** Biomass scarcity limits technological scalability for large-scale biogas-to-hydrogen projects

Souce: own elaboration.

Strategic pathways to address challenges and maximize opportunities. The strategic pathways presented in this study approaches a comprehensive yet ambitious framework for overcoming the barriers to biogas-based hydrogen deployment in Latin America, but their success depends on coordinated implementation and long-term commitment. Strengthening policy support and financial incentives is critical, as without explicit integration into national hydrogen strategies, subsidies, and carbon pricing mechanisms, biogas-based hydrogen will find it difficult to compete with electrolysis-based alternatives. Infrastructure expansion is equally essential, but the high capital costs of hydrogen transport and storage networks require regional cooperation and public-private investments to ensure cost-effective deployment. While technological advancements in reforming and microbial hydrogen production seem promising, scaling R&D initiatives and pilot projects requires stronger industry-academic partnerships and risk-sharing mechanisms. Additionally, integrating biogas-based hydrogen into rural and industrial applications presents an opportunity for economic diversification, but success centres on clear business models, stable policy frameworks, and investment security. These strategies must be implemented in parallel, as individual efforts will not be sufficient to transform biogas-based hydrogen into a commercially viable and scalable energy solution in the region.

CONCLUSIONS

Biogas-based hydrogen presents a viable pathway for renewable energy development in Latin America, enhancing the region's abundant biomass resources and growing demand for low-carbon energy alternatives. While technological advancements in reforming processes, microbial hydrogen production, and carbon capture solutions have been made, further research is required to optimize efficiency, reduce costs, and improve hydrogen storage and grid integration. Scaling up demonstration projects and establishing economic models that support financial sustainability will be critical to accelerating commercialization. These efforts must be supported by strong research collaboration, investment in infrastructure, and innovation in purification technologies to improve the feasibility of biogas-to-hydrogen systems.

Although the significant potential of biogas-based hydrogen, economic, policy, and infrastructure challenges are still the main obstacles for large-scale deployment. High capital costs and a lack of a well-developed hydrogen distribution network limit commercial expansion, while regulatory uncertainty and insufficient financial incentives reduce private sector interest. Moreover, many national hydrogen strategies prioritize electrolysis-based hydrogen, leaving biogas-derived pathways undervalued in long-term energy planning. To overcome these challenges, governments must integrate biohydrogen into national energy policies, implement carbon pricing mechanisms, and introduce tax incentives and direct subsidies to improve investment conditions. Furthermore, regional collaboration and the development of cross-border hydrogen trade frameworks could enhance market integration, making biogas-based hydrogen more economically viable and accessible within the region.

To unlock its full potential, biogas-based hydrogen must be positioned as a strategic component of Latin America's energy transition, complementing other renewable hydrogen sources. Countries with strong agricultural sectors, such as Brazil and Argentina, should prioritize biogas utilization, while Colombia and Mexico require regulatory clarity and investment support to drive market growth. Chile's leadership in hydrogen policy must be expanded to include biomass-based pathways where feasible.

This study concludes that with a coordinated approach to policy, investment, and technological development, Latin America has the potential to become a competitive global player in sustainable hydrogen production, contributing to decarbonization efforts and long-term energy security.

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Diminished work ability as a contributing factor for farmer's interest in switching to organic production

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Abstract. Previous studies suggest organic producers have diminished work ability, but it is unclear if this is due to pre-existing conditions or work exposures in organic production itself. The current study explored whether diminished work ability is a contributing factor to the interest in switching from conventional to organic production. The study used data from 2018, Finnish farmer questionnaire, analysed by machine learning - based approach and logistic regression modelling. Nearly half (46%) of the survey respondents (n = 2,948) had a diminished work ability score. Seventeen percent (n = 501) of the respondents reported being interested in switching to organic production. Farmers with diminished work ability had greater odds (OR 1.56, 95% CI: 1.26–1.92) for showing interest in switching. Those growing horticulture and special crops (vs. cereals) (OR 0.55) and those age 55+ years (vs. less than 35) (OR 0.51) showed less interest in switching. The interest in starting or expanding organic production was higher among those who already had an organic agreement on part of their farm (OR 5.7) and those who had other business activities on the farm (OR 1.36). In summary, this study suggests that diminished work ability predicts farmer's interest for switching to organic production. Measures to protect the health and well-being of farmers and workers during and after switching to organic production is critically important in achieving not only policy goals to increase organic production, but also good quality of life of farmers.

Key words: agriculture, logistic regression, machine learning, social sustainability, well-being at work.

INTRODUCTION

Well-being at work is an essential value expressed by farmers, and it is also one of the criteria in assessing the success of farm production (Mattila et al., 2008; Karikallio & Lahnamäki-Kivelä, 2023). Resilient food system requires strong social support, which is reflected in the EU's Farm to Fork strategy and social conditionality reform (European Commission, 2020).

Work ability is a widely used indicator for measuring well-being at work in many industries (Alavinia et al., 2007; Sell et al., 2009; Karttunen & Rautiainen, 2011; von Bonsdorff et al., 2011). It is based on theory that work ability reflects the balance between work demands and worker's resources (Ilmarinen 2006; Gould et al., 2008). Diminished work ability is more prevalent among farmers compared to other entrepreneurs or salaried workers (Saarni et al., 2008) indicating that the imbalance between worker resources and work demands is more frequent in farming than in other occupations (Gould et al., 2008). While the physical and mental health of an individual is an important element in determining work ability, it can also be influenced by skill development, motivation, work tasks, work environment and work management, as well as by family relationships and the surrounding community (Ilmarinen 2006; Gould et al., 2008). Reduced work ability is a strong predictor of increased sickness absence, disability pension, and mortality rate (Kujala et al., 2006; Alavinia et al., 2007; Sell et al., 2009; von Bonsdorff et al., 2011).

In Europe, the transition to organic production is seen as an important way to maintain biodiversity, combat environmental degradation, and to improve the welfare of farmed animals. The EU goal is to have 25% of agricultural land in organic production by 2030 (European Commission, 2020). In Finland, the area under organic production has been increasing, but is still far from the goal; in 2010, 3,939 farms (6.1% of all farms) and 7.5% of agricultural land were in organic production; in 2023, the respective figures were 4,153 farms (9.8% of all farms) and 13.7% of agricultural land (Finnish Food Authority, 2025). In addition to the environmental considerations, farmers are motivated to switch by the expected greater financial rewards in organic production (Pietola & Lansink, 2001; Karali et al., 2014; Trujillo-Barrera et al., 2016). Higher agricultural subsidies, premium prices, and lower production costs in organic farming may result in better profitability compared to conventional farming (Koikkalainen et al., 2011; Crowder & Reganold, 2015). Moreover, the productive performance of the Finnish organic farms has improved over the years (Kuosmanen et al., 2021).

Dessart et al. (2019) identified several behavioral factors that affect farmers' willingness to adopt sustainable farming practices, for example choices of neighboring farmers, opinions and actions of social referents, and a possibility to gain social status. Cranfield et al. (2010) highlighted that health and safety concerns also have a significant impact on farmers' willingness to switch to organic production. Some studies have reported that organic farming may have a positive impact on occupational health and safety of farmers and farm workers. Smit et al. (2007) found that organic farmers reported less wheezing with shortness of breath but found no effects of farming practices (organic/conventional) for asthma. Cross et al. (2008) found some indication of better mental health of workers on organic farms; however, three out of four measurements did not indicate differences between organic and conventional farms. Mzoughi (2014) found a positive impact of organic farming on life satisfaction whilst Khan et al. (2018) reported that organic farmers had less neurological symptoms than conventional farmers.

In our earlier studies among Finnish farmers, we have found no evidence that organic farming would have beneficial effects on occupational health and safety of farmers; including no differences in mental and musculoskeletal health symptoms (Mattila et al., 2022). Exposure to poisonous and irritating substances was less frequent, while exposure to vibration and mold was more frequent on organic farms (Mattila et al., 2022). Further, organic production had a negative association with work ability, i.e., diminished work ability was more prevalent among farmers practicing organic farming

(Mattila et al., 2020). However, these studies could not establish whether diminished work ability existed already before switching to organic production or developed after, due to organic farming exposures. Understanding this is essential for targeting preventive and well-being measures at work effectively.

The aim of the current study was to evaluate whether diminished work ability is a contributing factor to the interest in switching from conventional to organic production while controlling for sociodemographic and farm-related factors.

MATERIALS AND METHODS

This study was based on farm survey data collected by Kantar TNS Agri Oy in 2018 for the Finnish Ministry of Agriculture and Forestry. The survey, focusing on farm development plans, has been repeated every second year since 2006 with minor changes. Questions about work ability were included in the survey for the first time in 2018. Data collection was carried out using an online system and phone reminders. The survey sampling frame included all organic farms, all pig, poultry (with a minimum 100 chicken), sheep, and bovine farms, random sample of potato farms (500 farms, farm size over 1 ha), all sugar beet farms, random sample of field vegetable farms (600 farms, farm size over 1 ha), random sample of field berry farms (600 farms, farm size over 1 ha), random sample of crop farms (8,000 farms, farm size over 2 ha), all horse farms, and random sample of other plant production farms (1,000 farms). Crop, horticulture and other plant production farms were included in the sampling frame only if they had an email address. The selected animal farms were included even if they had no email address, in which case they were contacted by phone. The response rate was 17%: 4,442 farms in total, of which 3,739 were in conventional and 703 in organic production. After excluding farms that did not meet our analysis inclusion criteria, such as fully organic farms and farms with unclear organic status, our subset consisted of 2,948 valid observations (with no missing data).

Outcome variable

At the time of the survey in Finland, farmers were permitted to be partly in organic production, for example, have organic crop production whilst animal production was carried out by conventional methods. Therefore, the questions addressed each specified production sector separately, including interested in switching to organic production. The specified production sectors were dairy, beef, suckler cows/calves, suckler cows/slaughter animals, pork, egg, sheep, field vegetable, field berry, and plant production. Fully conventional farms were included in the analysis, and farms with no conventional production (i.e. fully organic or in the transition period) were excluded. Partly organic farms were included in the analyses; they are a special group that has already knowledge and experience of organic rules and methods.

The farmers were coded by interest in switching to organic production. Those answering 'interested in switching to organic production' in any of their specified production sectors they were coded as 'Yes' (for interested in switching). Otherwise, they were coded as 'No', not interested in switching to organic production. The distribution of the dichotomized outcome variable 'interested' is shown in Table 1.

Potential predictors

Work ability can be analyzed using several different methods. In Finnish population-based studies, the most typically used indicators are the Work Ability Index WAI), Work Ability Score (WAS), and Work Ability Estimate (Gould et al., 2008). In our study, we used the Work (Ability Score, which is a single question method in which a farmer self-assesses their current work ability compared with their lifelong best on a scale of 0 to 10. The English translation of the question used in the study was: 'On a scale of 0–10, how would you rate your current work ability? 0 means that you are currently unable to work at all and 10 that your ability to work is at its best'. The WAS is known to be strongly correlated with the Work Ability Index, which includes a large set of questions (Ahlström et al., 2010). El Fassi et al. (2013) recommends using the WAS method because of its user-friendliness, and satisfactory validity compared with the WAI index. In addition to work ability, potential predictors were related to farm and farmer characteristics, the farm's financial situation, and farm management choices (Tables 2–4).

Table 1. Frequencies of 'interested in switching to organic production' response variable

Classes of the 'interested' response variable	Class description	*n*	%
Yes	Farmers interested in switching to organic production	501	17
No	Farmers with no interest in switching to organic production	2,447	83
Total		2,948	100

Table 2. Description of the potential predictors for interest in starting organic production

Potential predictor	Categories	Description
Work Ability Score (WAS)	Declined Good	Farmer's own assessment of his/her current work ability compared with their lifelong best on a scale of 0 to 10, where 8–10 indicates good, and 0–7 declined, work ability
Main production sector	Crop production, Horticulture and special plants, Other plant production, Animal production	The main production sector of the farm based on the farmer's assessment
Farm size	<3 0 30–49 50–69 70+	Hectares of farmland (1 hectare = 2.47 acres)
Age	< 35 35–44 45–54 55+	Age of the farmer, years
Training	No Yes	Yes, if the farmer has received any training or advice on the specified topics[1]

Table 2 (continued)

Paid wage work	Yes No	Yes, if the principal farmer regularly works outside the farm either full-time or part-time
Profitability	Good Satisfactory Poor	Profitability of farming based on the farmer's assessment
Indebtedness	Not at all < 50,000 50,000–199,999 200,000+ Not known	Debt of farm business, €
Farm succession	Yes, certainly Yes, possibly No Not currently relevant	Do you have a successor who will continue production on your farm?
Organic agreement	No Yes	Yes, if part (but not all) of the production is already organic. The organic agreement is a commitment to follow rules of organic production and is a prerequisite for the organic production subsidies
Other business	No Yes	Yes, if the farmer had any other business activity in addition to basic agriculture in 2017
Developing crop farming	1…45	Adoption of practices to develop crop farming. Sum of responses to nine different actions[2] on a 5-point Likert scale: 1 = not at all….5 = very much

[1] Specified topics: finance; management and planning; marketing; risk management; feeding and animal care; silage production; other field cultivation; subsidies; computer and digitization skills; well-being at work; time management; employer skills; energy and environmental issues; inception of business operations; direct marketing and selling; food legislation.

[2] The specified actions were: production of crops (yield and quality) corresponding to market demand; knowledge of yields and production costs (€/tonne); use of risk management tools for crop production; improving the effectiveness of the use of nutrients by dividing the fertilization in the growing period; improving the crop yield by intensifying plant protection; basic improvements to fields like draining and liming; follow-up of mold toxins and contributory factors; use of early varieties for risk management; diversifying of cultivation using crop rotation and new plants for example.

The analysed data included 2,948 valid responses from Finnish farmers. Forty-six percent (1,366 farmers) of them had diminished work ability, and 54% (1,582 farmers) good work ability (Table 3). Seventeen percent (501 farmers) were interested in switching their farm to organic production, and 11% (54 farmers) of them had already partly followed organic production rules (Table 3).

Out of farmers expressing an interest in switching to organic production, 50% had declined work ability, 48% had animal farms, and 39% had farm size over 70 ha. They were most typically 45–54 years old, 89% had received training or advice in key topics, and most (69%) had no salaried work outside farming, but 58% had other business activities in addition to basic agriculture (Table 3). Profitability of these farms was typically (53%) on a satisfactory level and debt of farm business was between 50,000–199,999 € (Table 3).

Table 3. Frequencies of the potential class-scale predictors. The total number of persons $N = 2,948$

Potential predictor	Interest in switching to organic farming		
	No, *n* (%)[a]	Yes, *n* (%)[a]	Total, *n* (%)[1]
Work ability			
Declined	1,117 (46%)	249 (50%)	1,366 (46%)
Good	1,330 (54%)	252 (50%)	1,582 (54%)
Main production sector			
Crop production	815 (33%)	176 (35%)	991 (34%)
Horticulture and special plants	298 (12%)	40 (8%)	338 (11%)
Other plant production	290 (12%)	46 (9%)	336 (11%)
Animal production	1,044 (43%)	239 (48%)	1,283 (44%)
Farm size			
< 30	805 (33%)	119 (24%)	924 (31%)
30–49	488 (20%)	107 (21%)	595 (20%)
50–69	350 (14%)	79 (16%)	429 (15%)
70+	804 (33%)	196 (39%)	1,000 (34%)
Age			
< 35	157 (6%)	58 (12%)	215 (7%)
35–44	430 (18%)	112 (22%)	542 (18%)
45–54	799 (33%)	176 (35%)	975 (33%)
55+	1,061 (43%)	155 (31%)	1,216 (41%)
Training			
No	270 (11%)	53 (11%)	323 (11%)
Yes	2,177 (89%)	448 (89%)	2,625 (89%)
Paid wage work			
Yes	701 (29%)	157 (31%)	858 (29%)
No	1,746 (71%)	344 (69%)	2,090 (71%)
Profitability			
Good	332 (14%)	61 (12%)	393 (13%)
Satisfactory	1,281 (52%)	264 (53%)	1,545 (52%)
Poor	834 (34%)	176 (35%)	1,010 (34%)
Indebtedness			
Not at all	683 (28%)	92 (18%)	775 (26%)
<5 0,000	600 (25%)	132 (26%)	732 (25%)
50,000–199,999	567 (23%)	147 (29%)	714 (24%)
200,000+	541 (22%)	121 (24%)	662 (22%)
Not known	56 (2%)	9 (2%)	65 (2%)
Farm succession			
Yes, certainly	261 (11%)	38 (8%)	299 (10%)
Yes, possibly	698 (29%)	194 (39%)	892 (30%)
No	793 (32%)	84 (17%)	877 (30%)
Not currently relevant	695 (28%)	185 (37%)	880 (30%)
Organic agreement			
No	2,398 (98%)	447 (89%)	2,845 (97%)
Yes	49 (2%)	54 (11%)	103 (3%)
Other business			
No	1,282 (52%)	211 (42%)	1,493 (51%)
Yes	1,165 (48%)	290 (58%)	1,455 (49%)

[1] Percentages add up vertically in columns.

Table 4 gives the descriptive statistics for the variable 'developing crop farming' which is a sum of responses to nine different key actions explained in the Table 2. Both median and mean figures were a bit higher for those farmers who did not express interest in switching to organic farming (Table 4).

Table 4. Descriptive figures of the potential predictor 'developing crop farming'

	Interest in switching to organic farming	
	No	Yes
Developing crop farming		
Min	3.00	2.00
1st Q	15.00	15.00
Median	19.00	18.00
Mean	20.16	18.33
3rd Q	23.00	21.00
Max	45.00	45.00

Statistical analyses

We applied a machine learning - based approach, in which the aim was to maximize prediction performance. We used logistic regression as the basic model structure, explaining 'interest' probability with a subset of the potential predictors. The final logistic regression model was of the form

$$\Lambda^{-1}(\pi) = log_e \frac{\pi}{1-\pi} = logit(\pi) = \beta^T x \quad (1)$$

where y, x, and β denote 'interest', final predictors, and the corresponding model parameters, respectively. $E(y \mid x) = \pi$ and $\Lambda(z) = 1/(1+e^{-z})$ denote the cdf of the logistic distribution. Model selection was performed by constructing each possible predictor combination from the potential predictor set. For each predictor combination, 10-fold cross-validation (CV) was performed. For each fold, a model was fitted, and a performance metric was calculated. We chose accuracy as the performance metric, which is the overall proportion of correct predictions. For each predictor combination, a single CV accuracy measure was obtained by taking the mean of the 10 cross-validation accuracy measures. Finally, the predictor set corresponding to the maximum CV accuracy was chosen as the final predictor set. The whole CV model selection process was executed using three different threshold probabilities for predicting the 'interest' class.

The final predictor set's accuracy was compared to the no information rate, which is the larger proportion of the 'interest' dummy response. For the model to have any merit as a predictive model, its accuracy must exceed the no information rate. Otherwise, better predictive results are obtained by always simply predicting a single response class. For each predictor in the final predictor set, we calculated a variable importance metric by considering each predictor as the sole predictor and calculating the concordance index (c index). Finally, we constructed a simulated dataset of fixed predictor values to compare the response probabilities between work ability categories.

There was class imbalance between the response classes, as seen in Table 1. To tackle the issue, we applied upsampling of the minority class to match the class frequencies. This was done to investigate whether the model could better learn the minority class and not let the majority class dominate and introduce possible bias. The results were compared mainly using the receiver operating characteristic (ROC) curve and the area under the ROC curve (AUC). ROC is a graphical plot that measures the performance of a binary classifier at varying thresholds, and AUC is a metric constructed from the ROC curve.

Statistical modeling was performed using the R software (R Core Team 2023) and packages caret (Kuhn, 2008), dplyr (Wickham et al., 2023), ggplot2 (Wickham, 2016), and Metrics (Hamner & Frasco, 2018).

Research ethics

This study was conducted by Natural Resources Institute Finland (Luke), a government research institute for agriculture, forestry, and fishing (Finlex, 2014), which is committed to complying with the ethical principles of the Finnish National Board on Research Integrity TENK (Finnish National Board on Research Integrity TENK, 2012).

RESULTS

The cross-validation (CV) model selection process was performed using 0.50, 0.35, and 0.20 as the threshold probabilities. If the observation's prediction probability exceeds the threshold value, it receives the prediction class Yes. The threshold value can be modified to adjust for false positive and false negative rates. Table 5 shows best model predictor sets, accuracies, false positive rates, false negative rates, and the proportion of No class predictions for each threshold probability. For each threshold value, the model accuracy exceeds the no information rate. However, the margin is only small. The overall predictive merit of the models is therefore modest. This is at least partly because the response variable is imbalanced. When the threshold decreases, accuracy decreases, the false positive rate increases, and the false negative rate decreases. All in all, the false negative rate is large. This is because the total frequency of the Yes class is small. Most of the true Yes class observations are wrongly predicted to be No class. Our main priority was to maximize accuracy, and we did not have strict requirements for false positive or false negative rates. We therefore chose the threshold probability 0.5 and the corresponding predictor set as our final predictors.

Table 5. Model accuracy and no information rate

	Threshold 0.5	Threshold 0.35	Threshold 0.20
Predictors	work ability, main production sector, age, farm succession, organic agreement, other business, developing crop farming	work ability, profitability, indebtedness, training, farm succession, organic agreement	work ability, organic agreement
CV accuracy	83.9%	83.5%	83.2%
False positive rate	0.7%	1.5%	2.0%
False negative rate	91.6%	89.8%	89.2%
Proportion of No class predictions	98%	97.0%	96.5%
No information rate	83%		

Upsampling with replacement to investigate the possible domination of the majority class was used. After upsampling, the minority class frequency was increased from 501 to 2,447 to match the majority class frequency. The ROC curves for both the original and the upsampled datasets were calculated (Figs A1 and A2 in the Appendix, respectively). The ROC curves are practically identical. The x-axis (Specificity) measures the true negative rate, whereas the y-axis (Sensitivity) measures the true positive rate. There is a trade-off between sensitivity and specificity - when one increases, the other decreases, and vice versa. Thus, it is ultimately the decision of the applier of the classifier where they want to fix the threshold. The ROC curve shows that for whatever threshold for the original dataset classifier, there is a threshold for the upsampled datasets classifier for which the sensitivity and specificity pair gives equal values. The AUC values for the original and upsampled datasets were 0.681 and 685, respectively. Thus, both classifiers perform in the range of poor to fair. It is also concluded that upsampling did not provide a significant increase in performance. This might be due to lack of diversity of the original data, limitations of the classifier or data quality. Authors did not tackle any of these issues in this paper.

Table 6. Predictive variables for interest in switching to organic production in the final model. The total number of persons N = 2,948

	Frequencies (relative)	Min, max, mean, median	Model coefficient	OR (95% CI)	c-index
Work ability		-			0.52
Good	1,582 (0.54)		baseline		
Declined	1,366 (0.46)		0.44	1.56 (1.26, 1.92)	
Main production sector		-			0.54
Cereal crops	991 (0.34)		baseline		
Horticulture and special plants	338 (0.11)		-0.59	0.55 (0.38, 0.80)	
Other plants	336 (0.11)		0.03	1.02 (0.70, 1.50)	
Animals	1,283 (0.44)		-0.03	0.97 (0.77, 1.23)	
Age		-			0.58
<35	215 (0.07)		baseline		
35–44	542 (0.18)		-0.23	0.79 (0.54, 1.17)	
45–54	975 (0.33)		-0.40	0.69 (0.47, 1.01)	
55+	1,216 (0.41)		-0.67	0.51 (0.34, 0.76)	
Farm succession		-			0.60
No	877 (0.3)		baseline		
Yes, certainly	299 (0.1)		0.26	1.30 (0.85, 1.99)	
Yes, possibly	892 (0.3)		0.84	2.32 (1.74, 3.11)	
Not currently relevant	880 (0.3)		0.72	2.05 (1.51, 2.80)	
Organic agreement		-			0.54
No	2,845 (0.97)		baseline		
Yes	103 (0.03)		1.74	5.70 (3.72, 8.73)	
Other business		-			0.55
No	1,493 (0.51)		baseline		
Yes	1,455 (0.49)		0.31	1.36 (1.11, 1.68)	
Developing crop farming	-	2.0, 45.0, 19.9, 19.0	-0.04	0.96 (0.95, 0.98)	0.56

Table 6 shows information regarding the response and predictors. The total number of observations in the final data was 2,948. The point estimate odds ratio (OR) for work ability is 1.56 (Confidence interval, CI, 1.26, 1.92), i.e. those with diminished work ability had a higher probability of interest in switching to organic production. Horticulture production as the main production sector had a significant negative effect on interest, as did the farmer's age of 55 years or over. The answers 'Yes, possibly' and 'Not currently relevant' to the question concerning farm successor had a significant positive effect. Already having part of the farm in organic production was a strong predictor for switching also other parts to organic production. Having another business activity in addition to basic agriculture had a significant positive effect. Developing crop farming practices had a slightly but significantly, negative effect.

Table 7. Examples of the estimated probabilities (and confidence intervals) for 'interest' = yes

Work ability	Main production sector	Age	Farm succession (mode)	Organic agreement (mode)	Other business	Cultivation development (median)	Estimated probability of 'interest' = Yes
Diminished	Cereal crop production	35–44	4	No	Yes	18	0.305 (0.236–0.374)
Good	Cereal crop production	35–44	4	No	No	17	0.117 (0.131–0.223)
Diminished	Horticulture and special plants	35–44	4	No	Yes	18	0.195 (0.126–0.264)
Good	Horticulture and special plants	35–44	4	No	Yes	14.5	0.151 (0.097–0.205)
Diminished	Animal production	35–44	4	No	Yes	19	0.291 (0.223–0.359)
Good	Animal production	35–44	4	No	No	19	0.162 (0.122–0.202)
Diminished	Cereal crop production	55+	4	No	Yes	19	0.214 (0.159–0.270)
Good	Cereal crop production	55+	3	No	No	18	0.061 (0.041–0.081)
Diminished	Horticulture and special plants	55+	3	No	Yes	20	0.066 (0.039–0.093)
Good	Horticulture and special plants	55+	2	No	Yes	16	0.109 (0.068–0.150)
Diminished	Animal production	55+	3	No	No	20	0.084 (0.059–0.108)
Good	Animal production	55+	3	No	No	19	0.057 (0.038–0.076)

Table 7 shows some examples of the estimated probabilities with 95% confidence intervals for the interest in switching to organic production ('yes' class for interest). For example, when the cereal crop producer is between the ages of 35 and 44, the probability of choosing 'yes' is higher if the farmer has diminished work ability and other business in addition to basic agriculture (class 'yes') than if the farmer has good work ability and no other businesses (keeping successor issues and organic agreement in the mode class and developing crop farming in the median). The 95% confidence intervals do not overlap, which gives some indication of a significant difference between these probabilities. The same trend arises among animal producers of the same age group and among cereal producers in the older age group (55+).

DISCUSSION

Overall, 17% of farmers reported an interest in switching to practicing organic production, which is promising when considering the national goal for organic production. The challenge is that based on the results, farmers' diminished work ability was associated with an interest in switching from conventional to organic production. Based on the work ability theory (Gould et al., 2008), these findings suggest that an imbalance between work demands and farmers' personal resources is more frequent on farms interested in switching from conventional to organic production. The reasons behind this imbalance can be several. Diagnosed diseases, physically hard work, mental workload, lack of recovery from work, older age, economic uncertainties, and small farm size have been noted to be associated with declined work ability of farmers (Karttunen & Rautiainen, 2011; Mattila et al., 2020). Farmers may see organic farming as an interesting option, which could produce financial or well-being benefits that may improve their overall life situation. What actually happens to farmers' work ability after the transition to organic farming cannot be discerned from this study. However, the findings of previous studies (Mattila et al., 2020) have linked declined work ability with organic production, which suggests that switching to organic farming does not necessarily improve work ability of farmers. It should be noted that work ability explores the work system, particularly the balance between farmer's skills, motivation, and other resources in the relation to the demands at work. This is only one perspective to the well-being of farmers. E.g. Mzoughi (2014) has found that organic farming may have a positive impact on life satisfaction, and Cross et al. (2008) found some indication that workers on organic farms may be happier. Even if organic farming is challenging in many ways and requires new professional skills, there may also be positive health effects unique to organic farming (Brigance et al., 2018).

Well-being at work and the success of the farm business are intertwined. For example, mentally distressed farmers may perceive their financial situation worse than it actually is, which easily leads to unwillingness to invest and develop farming. In the long run this can lead to financial challenges and declining of their farm business (Gorgievski et al., 2010; Gorgievski & Ute 2016). Dijkhuizen et al. (2018) stated that entrepreneurs' well-being is a key factor in the long-term business outcomes (achieved subjective financial and personal success) and should be carefully maintained and improved. It is alarming that declined work ability is so frequent among farmers. It may have an effect also on their ability to achieve goals they have set for the switching process.

Based on this study, farmers who already had a part of their farm in organic production, and farmers who had another business activity in addition to basic agriculture, were more interested in expanding or converting to organic production. These findings are in accordance with earlier studies where other income sources or having diversified production predicted the interest in switching to organic production (Kallas et al., 2010; Mattila et al., 2018). Diversifying farm activities reduces risks (Kallas et al., 2010), and organic producers benefit particularly from specific direct sales channels (Rikkonen et al., 2017).

Production of horticulture or special crops as the main product and an older age (55+) had a negative effect on the interest in switching from conventional to organic production in the analysis. This result corresponds to the earlier findings among Finnish horticulture farms, only 12.1% were interested in switching to organic production; the interest was greater among smaller part-time enterprises (Mattila et al., 2018). Similarly, some previous studies have also found a younger age to be associated with the adoption of organic production (Burton et al., 1999; Kallas et al., 2010), but not necessarily in all farming sectors (Mattila et al., 2018). Moreover, organic farming tends to attract new entrants into the farming sector (e.g., Kallas et al., 2010; Väre et al., 2021; Farrell et al., 2022).

In this study, it was also found that farm succession planning was associated with switching to organic production; the likelihood of switching was more than doubled if the question about having an identified successor for the farm was answered as 'yes, possibly'. However, also situation where succession is 'not currently relevant' was associated with interest to switch to organic production. Plans for developing (conventional) crop farming practices had a slightly negative effect on the interest in switching. It should be noted that developing crop farming methods is very important also in organic production (like crop rotation), but by far, most of the organic farmland in Finland is used for cultivated grass production (Koivisto et al., 2020).

Between 2010 and 2020, 2,792 operators started and 1,661 gave up organic production (Finnish Food Authority, 2021). The reasons for exiting have not been analyzed, but the overall reduction in the number of farms is one reason, i.e., farmers do not necessarily revert to practicing conventional farming but retire or give up farming for other reasons. The potential role of declining work ability would be of specific interest in future studies. In Norway, Koesling et al. (2012) have studied the reasons for deregistering from organic production where farmers' decisions were influenced by financial issues, attitudes of the surrounding community, attraction of work outside farming, lack of information and communication about the benefits of organic production, and weaknesses in the implementation of regulatory changes. Gambelli & Brushi (2010) found that vegetable farms in particular had a high probability of exiting from organic farming due to technical and agronomical difficulties and difficulties in processing, distributing and marketing. They also found that farmers' age, farm location, and farm size influenced the probability of continuing organic farming. Organizing work during the transition process has been observed as a particular challenge. This may cause severe stress to farmers and make it challenging to meet the goals that they have set for the change (Navarrete et al., 2015; Chizallet et al., 2018; Väre et al., 2021). The transition period can be financially difficult, requiring an ability to learn and adopt new modes of operation (Koesling et al., 2004; Sipiläinen & Lansink 2005; Koesling et al., 2012; Navarrete et al., 2015; Chizallet et al., 2018).

Limitations

The final model's predictive power was not strong. This may be due to the underlying difficulty to capture the effect as there may be large natural variation. It is also possible that the class imbalance means more data is needed to increase the prediction performance. In Finland, the numbers of current organic farms are quite low, as are the numbers of those who are interested in switching to organic production, and thus the possibilities to obtain larger datasets are limited. Moreover, the definition of organic farm is not clear in all situations, which in our case resulted in excluding some farms from analyses.

The cross-sectional data offers a possibility to explore associations between variables, but not their causal relationships. This limitation must be kept in mind when interpreting the findings.

CONCLUSIONS

Declining work ability is common among farmers, and it predicts farmers' willingness to switch to organic production. Reasons behind declined work ability can be several, e.g. physical and mental workload, lack of recovery, older age, disabling diseases, and economic uncertainties. Measures to protect the health and well-being are critically important for long term business success, and health and safety should be integral parts of the switching process. Earlier studies suggest that organic farming requires even more skills in various areas, thus exposing farmers to more stress compared to conventional farming. Organising work and managing the workload are critical preventive measures on both conventional and organic farms, and they should be supported by advisory services. The need for such support should be further explored in future studies for farms with different development phases, capabilities, and goals, including the farmers' work ability limitations. In addition to ecological sustainability, principles of organic production also include social sustainability. In order to achieve future goals of increasing the share of organic production, social sustainability and the farmers' work ability must be considered.

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APPENDIX

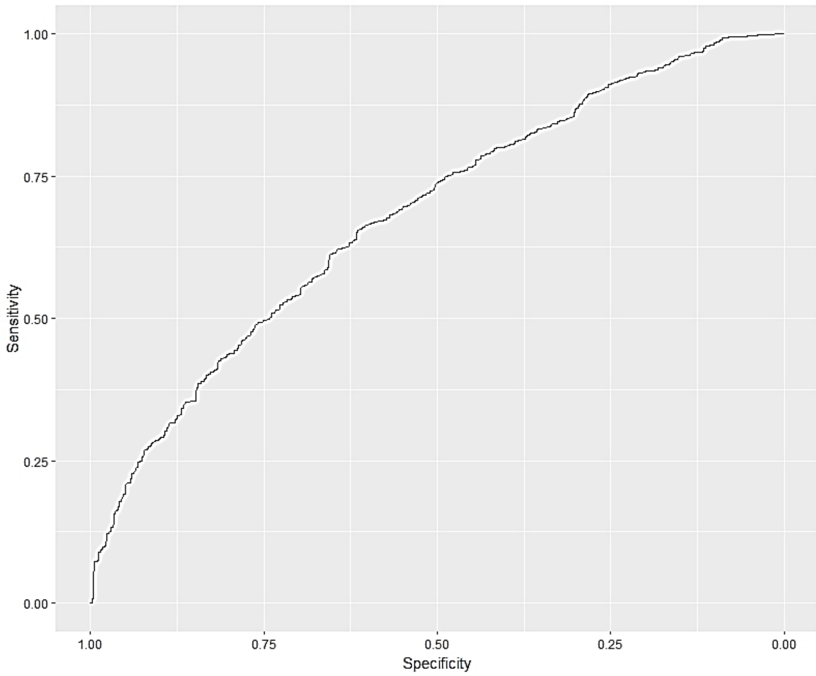

Figure A1. ROC curve showing the performance of the classifier based on the original dataset.

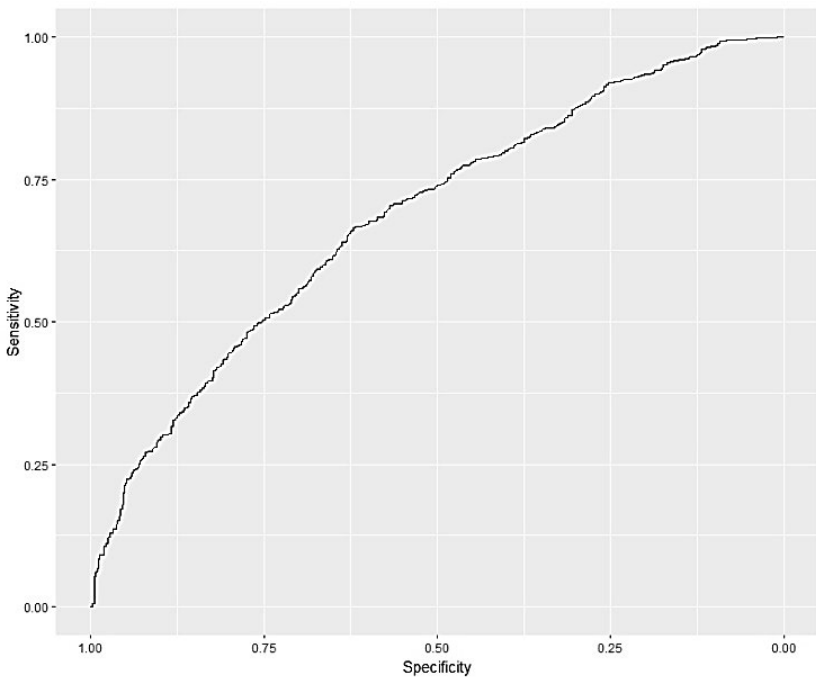

Figure A2. ROC curve showing the performance of the classifier based on the upsampled dataset.

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Temporal analysis of pasture vegetation cover in central-western Brazil using remote sensing

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Abstract. Brazil is the world's leading exporter of beef, consolidating beef cattle farming as an important branch of national livestock farming. The expansion of livestock farming and agriculture in recent decades has resulted in a notable increase in pasture areas in Brazil. However, the country faces the growing challenge of pasture degradation, a problem that threatens sustainability and food production. On the other hand, livestock farming in Brazil's Central-West region, the country's largest cattle-producing area, particularly in the state of Goiás, can cause environmental damage when sustainable practices are disregarded. Thus, the objective of this article was to evaluate pasture degradation, at different levels, in the Ribeirão Serra Negra Watershed, in the municipality of Piracanjuba, Goiás, Brazil. Using images from the Sentinel-2A orbital sensor, the NDVI (Normalized Difference Vegetation Index) vegetation index and the vegetation cover classes of pastures were obtained between 2017 and 2021. During this period, the results showed that more than 98% of the areas had some level of degradation, with an average coverage of 6,586.1 ha. There was an upward evolution in the levels of vegetation cover between 2017 and 2019, with the best pasture conditions predominating in 2019. These assessments help identify areas that require greater attention and often necessitate conservation practices and management plans. In this context, monitoring degraded areas is a practice that facilitates the improvement of existing pastures, promotes the rational management of inputs, conserves natural resources, and aligns with development programs focused on sustainability.

Key words: livestock grazing, pasture quality degradation, remote sensing, sustainable, vegetation indices.

INTRODUCTION

In Brazil, the Gross Domestic Product (GDP) of agribusiness accounts 24.8% of the country's economic performance. In 2022, despite a 6.39% decline in the agricultural sector, the livestock sector experienced growth by 2.11%. This progress is attributed with an increase in the gross value of production in the primary segment, linked to a reduction in input costs (CNA, 2023; CEPEA, 2023). According to FAO (2020), the country ranks seventh among the nations with the largest pasture areas, with land use covering 107 million hectares. Globally, it is the second-largest producer of beef, with a cattle herd approaching 224.6 million head.

At the state level, Goiás is the third-largest producer of cattle, accounting for 10.4% of the entire production chain (IBGE, 2023; Bolfe et al., 2024). The municipality of Piracanjuba is characterized by two well-defined seasons, with rainfall occurring between October and April and dry periods ranging from May to September. The average annual temperature ranges from 14 °C to 32 °C (Alvares et al., 2013; Embrapa, 2022; INMET, 2025). According to Instituto Brasileiro de Geografia e Estatística (IBGE, 2023), the number of cattle in the municipality between 2017 and 2021 was 232,567 and 206,000 head, respectively. The abrupt decrease in the cattle population occurred between 2019 and 2020, with a reduction of 26,000 head, from 231,000 to 205,000 animals.

Pasture degradation is a growing problem in various parts of the world, affecting agricultural and livestock productivity and compromising the health of ecosystems (Ferreira et al., 2024). This process results in the loss of soil nutrients, reduction of vegetation, and decline in biodiversity, which undermines the regeneration capacity of the affected areas (Shukla et al., 2019; Parente et al., 2019; Stabile et al., 2020). In Brazil, it is estimated that 60% of the areas (109.7 million hectares) are degraded, with the highest concentration occurring in the Central-Northern region of the country (Bolfe et al., 2024).

To mitigate the impacts of degraded areas, the country has adopted various strategies in partnership with other South American nations, such as pasture recovery through fertilization techniques, rotational grazing management, and the implementation of integrated crop-livestock-forest systems (CLF) (Ayarza et al., 2022). The use of more adapted forage species and the incorporation of agroforestry systems have also shown positive results, contributing to soil fertility recovery and increasing carbon sequestration. These initiatives are essential for reducing environmental damage and promoting more sustainable and efficient livestock farming (Arantes et al., 2018; Souza et al., 2019).

In addition to investing in research, Brazil encourages conservation actions and the adoption of technologies such as the use of satellite imagery coupled with different orbital sensors. These images, which can be accessed for free, offer multispectral bands that are processed through Remote Sensing techniques. Among the free satellite images available, those provided by the Sentinel-2 system stand out, characterized by the Sentinel-2A and Sentinel-2B sensors. These data, available since 2016, are widely used due to their 10 m pixel-1 spatial resolution and five-day revisit time. However, Sentinel-2A was launched in June 2015, becoming operational in 2016, and Sentinel-2B was launched in March 2017, becoming operational in 2018 (ESA, 2022).

In this context, the use of the Normalized Difference Vegetation Index (NDVI) has been the subject of recent studies for identifying and monitoring degraded areas (Hopping et al., 2018). The NDVI is a vegetation index applied to analyse vegetative activity, particularly the pasture cover and large crops (Sousa et al., 2022; Abreu et al., 2024).

Through the Annual Mapping of Land Cover and Land Use in Brazil project (MapBiomas, 2022), it is possible to obtain historical series of geographical information on land use and cover since 1985. The project provides collections of vector and raster data, updated and compiled annually (Lapig, 2022; MapBiomas, 2022).

In this regard, using the MapBiomas and Sentinel-2 databases, the aim of this study was to evaluate pasture degradation through the classes of pasture vegetation cover and biomass variation from 2017 to 2021. The objective of choosing this period was to evaluate the behavior of vegetative vigor in pastures with the aid of remote sensing during the COVID-19 pandemic scenario.

MATERIALS AND METHODS

Study area

The Serra Negra stream watershed is located in the municipality of Piracanjuba, in the Southern Goiás Mesoregion, and is situated within the Meia Ponte Microregion, between the geographic coordinates 17°10'55"S and 17°18'12"S; 49°03'07"W and 49°05'38"W (Fig. 1). Its territorial extension is 11,100 hectares, with 5,843.96 hectares (53%) corresponding to pasture areas. According to Köppen-Geiger, the climate is of the Aw type (Tropical humid), with an average annual precipitation of 1,600 mm (Alvares et al., 2013).

Data acquisition and preprocessing

Through the Copernicus program, orbital images from the Sentinel-2A sensor with a spatial resolution of 10 m were obtained, provided by the European Space Agency (ESA, 2022). The data acquisition, obtained from the Instituto Nacional de Meteorología (INMET, 2025), weather station A003 located in the southeastern region of the state, covered the first half of May, July, and October between 2017 and 2021, a period during which the pastures show differences in vegetative vigor due to the dry and wet seasons. May marks the end of the rainy season, making it useful for understanding the maximum biomass volume of plants after the long vegetative development period influenced by rainfall. July is characterized by extreme dryness, important for identifying the lowest biomass levels in pastures. October marks the beginning of rainfall, ideal for identifying the return of sprouting. In this sense, the average of these data was calculated annually, considering other criteria such as the absence of clouds (cloud cover < 30%) and minimal occurrence of fires (Embrapa, 2022).

The images covered two areas, T22KGF/T22KGG, and the MSIL1C-type bands used for preprocessing were B04 (red) and B08 (near-infrared). The multispectral bands were georeferenced and then atmospheric correction was performed using the Dark Object Subtraction (DOS1) method with the assistance of QGIS for desktop software version 3.16.11.

The land use and land cover vector files were obtained through the Mapbiomas platform. In this process, the evolution of pasture areas within the watershed in the period. Therefore, the watershed was obtained through automatic delineation using the Topodata elevation image, made available by the Instituto Nacional de Pesquisas Espaciais (INPE).

Vegetation index (NDVI) and vegetation cover (Vc)

The evaluation of vegetative vigor was carried out using the NDVI in the pre-processed satellite images proposed by Rouse et al. (1974), with the assistance of the raster calculator in the QGIS software for desktop version 3.16.11 (Eq. 1):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \quad (1)$$

where NDVI – Normalized Difference Vegetation Index; Red – red spectral band; NIR – near-infrared spectral band.

Table 1. Description and NDVI class intervals

Classes	Classification criteria
1 – Bare soil or water	NDVI ≤ 0
2 – Very Low	0 < NDVI ≤ 0.2
3 – Low	0.2 < NDVI ≤ 0.4
4 – Moderately Low	0.4 < NDVI ≤ 0.6
5 – Moderately High	0.6 < NDVI ≤ 0.8
6 – High	0.8 < NDVI ≤ 1

Source: Aquino & Oliveira (2012).

With the acquisition of the vegetation indices (NDVI), which range from -1 to 1, the data were classified according to Aquino & Oliveira (2012), structured into six classes (Table 1).

From the data extracted from the NDVI pixels, the levels of pasture degradation were classified. For this, the vegetation Cover (Vc) data were calculated (Eq. 2):

$$\mathrm{Vc} = \frac{(\mathrm{NDVI} - \mathrm{NDVIs}}{\mathrm{NDVIv} - \mathrm{NDVIs})} \times 100\% \quad (2)$$

where Vc – vegetation cover; NDVI – annual average NDVI value; NDVIs – lowest NDVI value found among bare soil pixels; NDVIv – highest NDVI value found among vegetation pixels.

The annual *Vc* values resulting from Eq. 2 were reclassified according to Gao et al. (2006) into 5 different levels of pasture degradation (Table 2).

Table 2. Vegetation cover classification (Vc)

Classification	Vc
Un-degraded (UD)	Vc > 90%
Lightly degraded (LD)	90 ≥ Vc >75%
Moderately degraded (MD)	75 ≥ Vc > 60%
Severely degraded (SD)	60 ≥ Vc > 30%
Extremely Severely degraded (ESD)	Vc ≤ 30%

Source: Gao et al. (2006).

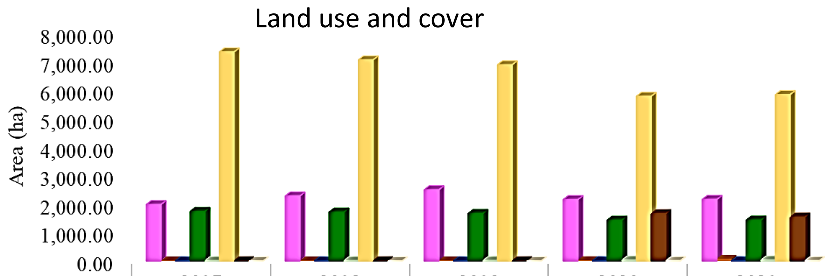
The NDVI and Vc classifications were subjected to descriptive statistics, analysis of variance (ANOVA). Based on the Vc values, biomass analysis was conducted between 2017 and 2021 to assess the increase or decrease (Eq. 3).

$$\mathrm{Vc} = \mathrm{Vc}\,(2017) - \mathrm{Vc}\,(2021) \quad (3)$$

RESULTS AND DISCUSSION

The land use and land cover area, in hectares (ha), in the Serra Negra stream watershed, located in the municipality of Piracanjuba, GO, is represented in Fig. 1. The term 'agriculture' refers to areas planted with annual crops, such as soybeans, corn, sorghum, among others, cultivated on a large scale. ‘Pasture’ is associated with areas designated for livestock farming, with the cultivation of various pasture species that have a perennial cycle and alter their biomass according to the environmental conditions to which they are exposed. Areas with native vegetation, with minimal biome modifications, are represented by ‘forest’, while ‘forestry’ refers to areas with the cultivation of forest species. 'Water body' is used for areas with apparent water resources.

'non-vegetated area' refers to targets such as impermeable surfaces (infrastructure, urban expansion, or mining). The ‘non-forest natural formation’ includes grassland formations with a predominance of herbaceous layers (e.g., scrubland, open grassland, and rocky fields). The ‘land use mosaic’ is characterized by agricultural use, where agriculture and pasture are not distinguished (MapBiomas, 2022).



	2017	2018	2019	2020	2021
Agriculture	1,980.34	2,282.34	2,500.84	2,155.04	2,161.27
Non-vegetated area	19.30	21.13	21.99	28.05	79.00
Water body	4.19	4.10	4.70	6.24	6.24
Forest	1,737.72	1,714.59	1,665.19	1,431.31	1,431.99
Non-forest natural formation	11.46	11.28	13.68	30.36	33.26
Pasture	7,343.60	7,063.16	6,891.91	5,784.13	5,843.96
Forestry	5.50	5.50	3.79	1,659.03	1,538.17
Mosaic of uses	0.00	0.00	0.00	7.95	8.21

Figure 1. Land use and land cover in the Ribeirão Serra Negra stream watershed in the municipality of Piracanjuba, Goiás, Brazil.

However, the temporal analysis showed that pasture areas decreased, dropping from 66% of land occupation in 2017 to 52% in 2021. During this period, it was observed that silviculture experienced the largest growth in the interval, approximately 13.8%. This increase is related to the potential of the Cerrado biome and the adoption of sustainable practices such as the Integrated Crop-Livestock-Forest System (ICLF) and the national Low Carbon Agriculture Program (ABC Plan), approved in 2011 (EMBRAPA, 2020). Also noteworthy is the promotion of conservation practices developed by Emater-GO, which, in a survey conducted in 2020 and 2021, identified between 81 and 244 different practices in the Southern region of the state of Goiás. These practices ranged from pasture management, production and property management, guidance on spring protection, pasture formation/renewal, and environmental management on the property, resulting in an improvement in the percentage of silviculture (Emater, 2022).

This increase is related to the potential of the Cerrado biome and the adoption of sustainable practices such as the Integrated Crop-Livestock-Forest (ICLF) (Embrapa, 2020). Over the last 35 years, pastures in Brazil totalled 64 Mha, with 18 Mha of pre-existing pastures being converted into agriculture and silviculture (Feltran-Barbieri & Féres, 2021). The average area of ‘agriculture’ over the years, the second most extensive class, was 2,215.97 ha. The other land uses and land covers showed no significant variations, with changes of less than 1% at the end of the 5-year period.

Other land uses and covers did not show significant variations, with changes of less than 1% by the end of the 5-year period. The average of 'agriculture' over the years, the second most widespread class, was 2,215.97 ha. In the Cerrado, the Non-vegetated area refers to targets such as impermeable surfaces (infrastructure, urban expansion, or mining). The 'non-forest natural formation' includes grassland formations with a predominance of herbaceous layer (scrubby field, clean field, and rocky field). The land 'use mosaic' is characterized by agricultural use, where agriculture and pasture are not distinguished (MapBiomas, 2022).

Through the mapping of pastures and the application of NDVI, vegetative vigor was evaluated (Fig. 2). It was observed that the variability of vegetation indices showed symmetric dispersion in most years, according to the classification by Aquino & Oliveira (2012). In 2017 and 2021, the greatest variability was observed, ranging between the 'moderately low' and 'high' classes.

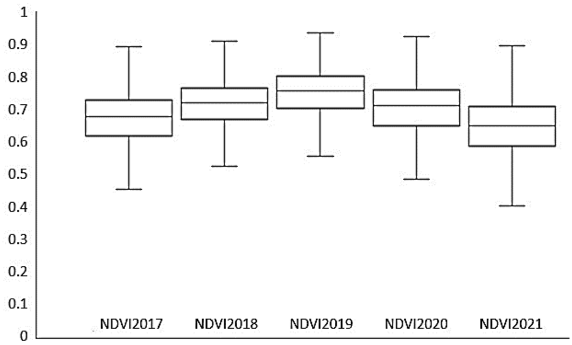
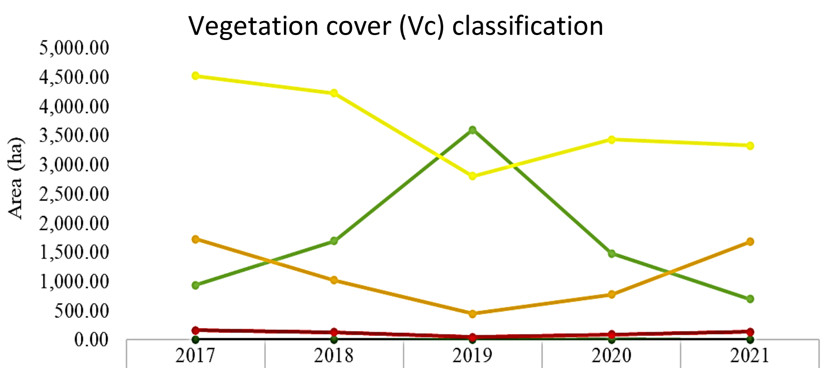


Figure 2. Variation of vegetative vigor, determined by the Normalized Difference Vegetation Index (NDVI), as a function of temporal variation in the Serra Negra stream watershed in the municipality of Piracanjuba, Goiás, Brazil.

The best year was represented by 2019, with a 'moderately high' average, NDVI values close to 0.8, and a slight amplitude, compared to the other years. There were no differences over time regarding the pasture degradation classes, considering that the results were within the variance limits.



	2017	2018	2019	2020	2021
Un-degraded	0.00	0.05	3.72	4.49	1.10
Lightly degraded	935.26	1,689.20	3,597.78	1,476.25	697.19
Moderately degraded	4,517.12	4,221.77	2,799.77	3,431.22	3,323.31
Severely degraded	1,727.01	1,021.95	446.61	776.81	1,682.57
Extremely Severely degraded	164.22	130.18	44.04	93.87	139.80

Figure 3. Evolution of pasture degradation classification from 2017 to 2021 in the Ribeirão Serra Negra Watershed in the municipality of Piracanjuba, Goiás, Brazil.

The pasture degradation classification highlighted the predominance of the 'moderately degraded' class throughout the period, with areas exceeding 2,700 ha (Fig. 3). 'Non-degraded' areas represented discrete values, accounting for less than 2% of the total evaluated area over the 5 years, and were not considered representative. On the other hand, more than 98% of the areas exhibited some level of degradation, with an average of 6,583.10 ha.

All pasture classes with some level of degradation showed reductions in the values obtained in 2021 compared to those in 2017, resulting in a slight increase in the level of non-degraded pastures over the study period. However, although variations in the data were observed over the years, no statistically significant differences were found between the years (p-value ≥ 0.05) (Table 3). The lack of significance can be explained by the wide variability within the 'lightly degraded', 'moderately degraded', and 'severely degraded' classes, which makes it difficult to identify significant differences between classes.

Table 3. Analysis of variance for the different pasture classes evaluated from 2017 to 2021 in the Ribeirão Serra Negra Watershed in the municipality of Piracanjuba, Goiás, Brazil

Source of variation	GL	SS	MS	F	*p*-value	F critical
Between groups	4	418,246.44	104,561.61	0.04	1.00	2.87
Within groups	20	52,175,454.52	2,608,772.73	-	-	-
Total	24	52,593,700.97	-	-	-	-

The increase in the class of lightly degraded pastures in 2019 was driven by better rainfall distribution and higher average temperatures in the early months of the year, with considerable precipitation volumes maintained until May (Table 4). In other years, there was less precipitation between January and May, a period characterized by the establishment and greater vegetative development of the crops in the field. It is also noteworthy that the higher rainfall volumes between October and December, observed in 2017, 2018, and 2020, were not sufficient to reduce the level of pasture degradation, as although the start of rainfall was late in some years, after the onset of precipitation, the plants began the sprouting period similarly. Only after a few days of the plants' exposure to reduced water availability could differences in vegetative growth be identified. This limitation typically begins in the months of April and May.

Studies indicate that higher levels of precipitation are associated with increased soil moisture, both at the surface and in depth, which results in higher NDVI values, as plants would have sufficient water availability to perform photosynthesis (Ribeiro et al., 2019; Jucá et al., 2019; Souza, 2019). Similarly, Rezende (2023) highlights that, during the dry season, vegetation indices show greater sensitivity to soil moisture variations, indicating that when water becomes a limited resource, it is possible to obtain more responsive NDVI values to the conditions to which the plants are exposed. Thus, the lower level of precipitation in May resulted in reduced vegetative growth of pastures in the years 2017, 2018, 2020, and 2021.

Besides the water conditions, the reduction in the level of degraded pastures is associated with farmers' adoption of the Barreirão System, an integration model developed by Embrapa Arroz e Feijão, with the Fazenda Barreirão, located in the municipality of Piracanjuba, GO, serving as the model for implementing this system (Kluthcouski et al., 1991). The Barreirão system proposes the renewal of pastures through the intercropping of annual crops with pastures (Vilela et al., 2019). Due to the success of this system for the recovery/renewal of degraded pastures, the states of Mato Grosso, Minas Gerais, and Goiás have adopted the Barreirão system as an official government program. In this context, since the launch of the Barreirão system, there has been an increase in the adoption of pasture renewal practices by regional producers, justifying the improvement. Other sustainable policies, such as the national Low Carbon Agriculture Program (ABC Plan), have also been adopted by regional producers.

Table 4. Meteorological data from the southeastern region of the state of Goiás, obtained at station A003, during the period from January 2017 to December 2021 (INMET, 2025)

Months	2017		2018		2019		2020		2021	
	Prec.[1]	Temp.[2]	Prec.	Temp.	Prec.	Temp.	Prec.	Temp.	Prec.	Temp.
Jan.	219.2	23.8	224.0	23.6	182.8	24.7	204.6	24.6	125.4	24.0
Fev.	64.0	23.9	155.6	23.8	153.4	24.5	354.8	24.2	297.8	23.7
Mar.	112.8	23.9	103.2	24.4	251.6	23.8	114.8	24.1	150.4	23.5
Apr.	112.2	23.5	88.6	22.0	97.6	23.5	41.8	23.0	49.6	22.3
May	75.4	21.8	4.6	20.0	92.4	22.0	9.0	19.6	1.6	21.2
Jun.	4.2	19.7	0.4	20.6	0.0	19.8	0.0	20.6	3.2	20.0
Jul	0.0	18.0	0.0	19.8	0.2	19.3	0.0	20.9	null[3]	null
Aug.	0.0	22.1	2.0	22.1	0.0	22.1	0.0	22.0	null	null
Sep.	10.8	23.9	74.4	23.7	15.4	26.4	8.6	26.0	null	null
Oct.	58.6	25.9	125.8	24.7	38.0	26.0	138.0	26.4	null	23.9
Nov.	334.8	23.6	287.2	23.4	164.0	25.1	165.8	24.7	null	23.9
Dec.	226.4	23.6	143.2	24.6	317.0	24.3	300.8	24.4	174.2	24.1
Total	1,218.4	-	1,209.0	-	1,312.4	-	1,338.2	-	802.2	-

[1]Prec.: monthly precipitation obtained in millimeters (mm); [2]Temp.: monthly average temperature obtained in degrees Celsius (°C); [3]null: precipitation and temperature data not provided by the weather station.

All classes showed reductions; however, they did not present statistically significant differences. The severely degraded class showed a reduction of 5.7%. Nationally, severely degraded pastures decreased from 34.3% to 25.2% between 2010 and 2018 (MAPA, 2020). This is due to the adoption of sustainable policies by farmers, such as the National Low Carbon Agriculture Plan (ABC Plan).

Fig. 4 shows the occurrences of degradation classes through spatial distribution. It is worth noting that the 'severely degraded' class decreased considerably in the first three years (1,280 ha). In 2019, the slightly degraded class showed the highest occurrence, followed by moderately degraded pastures, reflecting the year with the best pasture quality in the watershed.

Since 2019, there has been a decrease in lightly degraded pastures and an increase in moderately degraded and severely degraded classes. It is inferred that these negative results are a reflection of the Covid-19 pandemic on agricultural input costs (Lizot et al., 2023). The authors report a global average cost increase of 39.47% and a weighted average increase of 34.7%, mainly affecting small rural properties due to their limited negotiating capacity and smaller-scale purchases.

Among the inputs that saw an increase, chemical fertilizers essential for the implementation of crops such as corn, sorghum, and pasture management stand out. According to the World Health Organization (WHO), the forecast for a global trade setback was 32% (Porsse et al., 2020). However, according to the International Monetary Fund (IMF, 2021), the setback exceeded 35%.

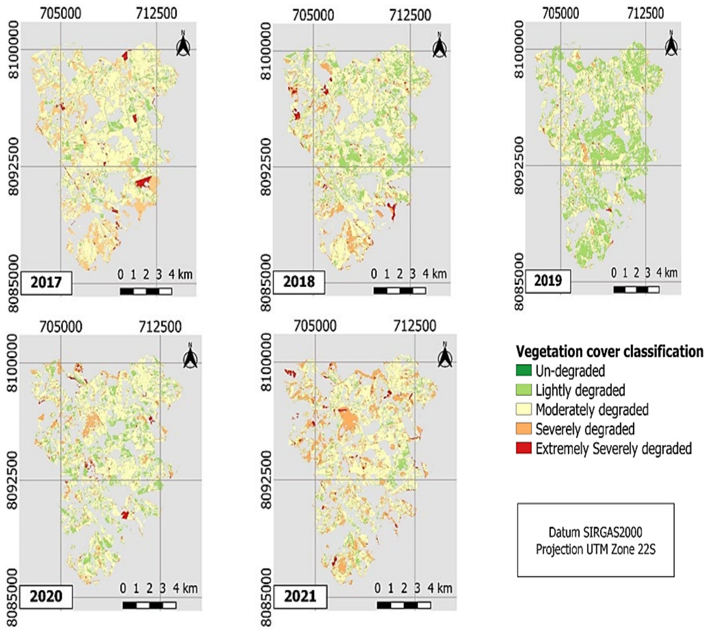


Figure 4. Occurrence of degradation classes in pastures of the study areas from 2017 to 2021.

For livestock, a higher occurrence of non-degraded pasture is expected. However, the presence of this class was negligible, with few events occurring, representing an outlier with a negative aspect, being imperceptible in the spatial variability. This scenario reflects the need for proper management in the existing areas. On the other hand, the low representativeness of extremely degraded pastures characterizes a positive outlier, meaning there are fewer areas to recover, given that recovery plans are costly.

The biomass results from 2017 to 2021 are shown in Fig. 5. It is observed that due to the predominance of the yellow color, there were no changes. The 'No Changes' class represented approximately 62.1%, equivalent to 3,629 ha.

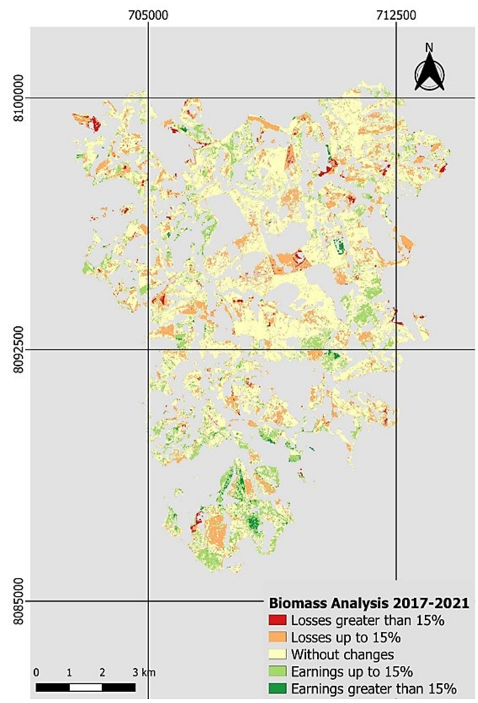


Figure 5. Analysis of biomass gains and losses between 2017 and 2021 in the Ribeirão Serra Negra Watershed in the municipality of Piracanjuba, Goiás, Brazil.

In the comparison between biomass gains and losses, the data showed that losses were greater, with area values close to 1,269 ha, while gains were approximately 945 ha. The largest losses were recorded in the ‘losses up to 15%’ class, and the greatest gains in the ‘gains up to 15%’ class.

From a socioeconomic perspective, pasture evaluations through vegetative vigor and vegetation cover conditions proved to be a valuable tool for producers and the implementation of public policies, guiding them to areas that require more attention and, often, need conservation practices and management plans in this watershed, a tributary of the Meia Ponte River. In this regard, monitoring degraded areas is a practice that enables the improvement of existing pastures, allowing for the rational management of inputs, conserving natural resources, and supporting programs like the 2023/2024 Safra Plan, which aims at sustainability (MAPA, 2023).

CONCLUSION

The different land use and land cover classes for the Serra Negra stream watershed remained largely unchanged during the study period (2017 to 2021). For the pasture class, more than 98% (6,583.10 ha) of the areas showed some level of degradation, with the best vegetation cover conditions occurring in 2019, a period characterized by the adequate distribution of rainfall in the first months of the year (from January to May). Remote sensing techniques involving the NDVI index and Vc analysis were effective in monitoring pasture degradation and the results showed associations with climatic conditions.

The transformations observed in the pasture class were primarily influenced by climatic conditions, rather than by public policies adopted in the context of the Covid-19 pandemic. Thus, for improvements in pasture quality, livestock farmers should adopt appropriate management practices to maintain vegetation in stressful conditions, such as soil fertilization, pasture renovation using adapted forage species, implementation of rotational grazing techniques, and the adoption of integrated systems. These actions not only promote pasture recovery but also contribute to the protection of the watershed's water resources, ensuring the maintenance of local ecosystems and promoting long-term environmental stability.

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Evaluation of chest circumference in 3D lateral images of dairy cattle farming for body mass prediction

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Abstract. The advancement of precision livestock farming has underscored the importance of developing innovative and non-invasive methods for monitoring animal health and productivity. In this context, this study evaluated the application of computer vision to estimate the body mass (BM) of Holstein-Friesian dairy cows using 3D images captured laterally with the Intel RealSense D435i depth camera. The methodology involved correlating chest circumference (CC) measurements obtained in the field with those derived from lateral 3D images. A total of 250 animals were analyzed, with BM ranging from 420 to 855 kg, and the relationship between CC and BM was modeled using regression techniques. The results indicated a coefficient of determination ($R^2 = 0.88$) and a mean absolute percentage error (MAPE) of 3.94% for CC measured in the field. For CC derived from 3D images, R^2 was 0.847, with an MAPE of 5.29%. Although the 3D image-based method showed a slight reduction in accuracy, it demonstrated significant potential as a non-invasive and efficient alternative for estimating BM in dairy cows. Furthermore, the study highlights the role of 3D imaging technologies in acquiring detailed morphological data, enabling a more comprehensive understanding of body composition dynamics over time. These findings reinforce the potential of integrating digital technologies into dairy farming, promoting sustainable, precise, and labor-efficient management practices.

Key words: 3D images, computer vision, dairy cattle farming, non-invasive body mass estimation.

INTRODUCTION

Precision livestock farming has gained prominence in modern agriculture, offering innovative solutions for the efficient and sustainable management of herds. However, the diversity of production environments still poses a significant challenge to the implementation of intelligent systems for monitoring animal conditions (Qiao et al., 2023). In this context, the use of automation and sensor-based systems has proven to be a promising tool, enabling real-time individualized monitoring of cows. These systems also allow for the implementation of early warning alerts, facilitating managerial decision-making to mitigate anomalies and improve productivity. One of the key parameters in this monitoring process is body mass (BM), which plays a crucial role in assessing herd health status (Gebreyesus et al., 2023).

Measuring the body dimensions of cattle is a useful method for assessing their health and growth (Weales et al., 2021), and monitoring BM plays a crucial role in tracking productivity while providing insights into the energy balance of individual lactating cows (Mäntysaari & Mäntysaari, 2015).

Traditional methods, such as weighing with scales, while accurate, often require the physical restraint of animals, leading to stress and associated risks for both cattle and operators (Xavier et al., 2022). Additionally, weighing devices may present issues related to calibration accuracy or proper functioning due to environmental conditions and the need for a dedicated team to organize and oversee the weighing process (Tasdemir et al., 2011). Moreover, these scales are relatively expensive, and their electronic components are susceptible to damage in the harsh environment, which is exposed to manure and urine and in direct contact with cows (Dickinson et al., 2013).

In this context, computer vision technologies emerge as an innovative alternative, enabling data acquisition in a less invasive manner and with higher frequency, allowing for more dynamic and efficient herd management (Le Cozler et al., 2019). Unlike conventional methods, such as manual weighing that relies on physical systems, computer vision can be applied continuously without the need for direct interaction with animals, reducing stress and improving animal welfare.

With the advancement of computer vision technologies, new approaches have been developed to capture and analyze the morphological characteristics of cattle in an automated and precise manner. These technologies can measure parameters such as chest circumference (CC), which, among other variables, stands out as one of the most reliable indicators of BM (Heinrichs et al., 1992; Martins et al., 2020).

This reliability of CC as a predictor has been reinforced since the study by Davis, Swett, and Harvey (1961), who analyzed 46 studies available up to that time and found that, in 35 of them, CC was identified as the best predictor of BM in cattle, being even used as the sole variable in several models. The authors also highlighted that adding other variables to CC-based models did not result in significant improvements in estimation accuracy, and the reported correlation coefficients often exceeded 0.95, indicating a highly robust statistical relationship with BM. This level of precision was so remarkable that it led to the development of specific measuring tapes designed for direct weight estimation based on CC.

The relevance of CC as a predictor of BM remains widely accepted in the current literature and is still employed in several studies that assess cattle body weight through indirect methods. In addition to its accuracy, CC stands out for being an easily measurable variable with practical applicability in production systems, especially on farms that lack scales or animal restraint structures. It is speculated that this strong correlation is due to anatomical and physiological factors, since the thoracic region houses large-volume organs such as the rumen, lungs, and heart, and also represents an area of significant muscular development and structural stability, as also reported by Heinrichs et al. (1992).

Considerable research on the prediction of BM in cows has been conducted, achieving promising results through innovative approaches. These studies can be divided into two main categories: methods based on traditional morphometric measurements and technologies involving computer vision and machine learning. Traditional methods utilize physical variables such as chest circumference (CC), body length (BL), and hip height (HH), applied in statistical models to estimate BM. While widely validated, these methods have limitations due to the need for direct contact with the animals, as seen in the following studies (Heinrichs et al., 1992; Kashoma et al., 2011; Dickinson et al., 2013; Mäntysaari & Mäntysaari, 2015; Lukuyu et al., 2016; Heinrichs et al., 2017). On the other hand, computer vision technologies enable the extraction of morphological features through images captured by RGB cameras, depth cameras, and drones, integrating this information into machine learning models for improved prediction accuracy, as demonstrated in studies such as (Tasdemir et al., 2011; Song et al., 2018; Xavier et al., 2022; Gebreyesus et al., 2023). By combining established methods with technological innovations, these approaches have significantly contributed to the advancement of digital and precision livestock farming.

The 3D imaging technologies have solidified their position as promising tools in the morphological analysis of cattle, enabling significant advancements in the precision and richness of the data collected. By utilizing depth cameras, it is possible to capture detailed information about body structure and its variations over time, supporting a dynamic and integrated approach to precision livestock farming (Ferreira et al., 2022). This ability to record high-resolution three-dimensional data not only enhances BM estimation but also opens new possibilities for continuous monitoring of body composition, such as changes in energy reserves, growth, and gastrointestinal tract filling, providing a broader and more detailed view of animal physiology at different production stages (Xavier et al., 2022).

Over the last decade, and more recently, various non-invasive approaches have been proposed for predicting BM in cattle, with particular emphasis on methods based on digital imaging. Tasdemir et al. (2011) used 2D photographs taken from different angles to extract morphometric measurements and estimate the body weight of Holstein cows using linear regressions. However, their method required multiple cameras, a controlled lighting environment, and calibration procedures, which may hinder large-scale adoption. Advancing to the use of depth sensors, Kuzuhara et al. (2015) applied a 3D camera to capture dorsal images and estimated weight based on geodesic measurements of the back, achieving promising results. Although effective, this approach did not directly incorporate conventional morphometric measures such as CC, which is widely recognized in the literature as one of the most robust predictors of BM. Similarly, Na et al. (2022) proposed an automated system using RGB-D images captured from a top view and machine learning techniques, extracting descriptors such as body area and volume. While efficient, the method also did not consider variables traditionally used in precision livestock farming, such as CC. In light of this, the present study proposes an alternative approach based on laterally captured 3D images, aiming to combine the reliability of classical morphometric methods with the technological advances of computer vision, offering a more practical, accurate, and production-compatible solution.

Building upon the advancements in computer vision applications for bovine morphometry, Peng et al. (2024) proposed a method to estimate CC based on RGB-D lateral images captured by a ZED2i camera. By utilizing keypoint detection with the YOLOv8-Pose model and mirroring symmetry, the authors reconstructed the thoracic shape to estimate CC, achieving promising results. However, the methodology requires precise anatomical labeling and computationally complex steps. In contrast, the present study proposes a more direct approach, based on the extraction of CC from 3D images captured laterally in a production environment. Although the current step still relies on manual annotations, the adopted strategy demonstrates potential for future automation of the process, combining operational simplicity and practical applicability with accuracy in predicting BM.

Despite the recognition of CC as a robust predictor of BM, studies validating its estimation from 3D images captured laterally in field conditions remain scarce. This limitation highlights an important gap in the use of computer vision applied to automated morphometric measurement of bovines, particularly regarding the integration of scientific accuracy and practical applicability. Therefore, this study aims to assess the application of computer vision in estimating the BM of Holstein-Friesian dairy cows, using 3D images captured laterally with the Intel RealSense D435i depth camera. From a scientific perspective, the goal is to validate the efficiency of estimating CC from 3D images, analyzing its correlation with the actual BM of the animals, and contributing to the advancement of non-invasive techniques in precision livestock management. From a practical standpoint, the work proposes a viable, lower-cost alternative that can be applied in the field for the automatic measurement of BM, reducing the need for animal containment and optimizing management in modern dairy systems.

MATERIALS AND METHODS

This research followed all experimental procedures approved by the Animal Ethics Committee (CEUA) of the Federal University of Lavras, in accordance with Protocol Number 8093310125.

The study was conducted on an experimental dairy cattle farm located in the municipality of Ijaci, in the state of Minas Gerais, Brazil, at coordinates 21°09'40.1"S 44°55'45.3"W (Fig. 1), involving lactating Holstein-Friesian cows. A total of 250 records were used for analysis. The cows were housed in a Tie-stall system, with individual sand beds and continuous mechanical ventilation operating 24 hours a day. Fan speed was automatically adjusted by ambient temperature sensors to ensure adequate thermal comfort. Additionally, sprinklers were manually activated during the day, generally between 7 a.m. and 5 p.m., in intermittent cycles, especially on hot days, such as those recorded during the experimental period.

Figure 1. Farm location.

The cows had continuous access to water on demand, with one water trough available for every two stalls, regulated by a float valve. Additional water troughs were available in both the holding pen and the milking parlor. Feeding was carried out using a Total Mixed Ration (TMR). During the data collection period, due to concurrent nutritional experiments conducted on the farm, wooden dividers were used to individually control each cow’s access to feed. Outside of these periods, feeding is carried out in groups.

Although the study involved occasional animal restraint procedures to obtain actual BM and CC measurements using a measuring tape - which served as reference values for model validation - these practices were already part of the farm's routine, especially during data collection for other nutritional and zootechnical experiments. All management procedures followed animal welfare principles, ensuring comfort, access to water and feed, as well as appropriate environmental conditions. It is also worth noting that the approach proposed in this study, based on computer vision, aims precisely to provide a less invasive and more efficient alternative, with the potential to replace manual procedures requiring physical restraint in future field applications.

After milking, the cows were managed towards an Intel® RealSense™ Depth Camera D435i to capture 3D images, located near the entrance to the weighing area where there was a Tru-Test digital scale, model EziWeigh5, with a 5 kg resolution for the collection of their BM. The camera was positioned 1.5 meters from the animal, along the path to the scale, at a height of 1 meter from the ground, to capture lateral videos of the cows using the Intel RealSense Viewer software (version 2.54.1), as shown in Fig. 2. The camera was used with its default settings, without additional calibration adjustments. The reliability of the depth estimates was verified in a practical manner by comparing them with objects of known dimensions placed at varying distances. This visual verification ensured that the captured images accurately reflected the animals body structure in the field environment.

Figure 2. Camera installed to capture side images.

This handling procedure took place after the cows exited the first milking of the day, which started at 5:00 a.m. As the animals approached the camera, a video capture was initiated to collect a sequence of images, from which a frame could later be selected that best displayed the full lateral body of the animal. An example of one of the captures made by the RGB and depth cameras can be seen in Fig. 3.

Recording videos with a depth camera allows for the capture of dynamic and continuous information about animal movement, enhancing data accuracy and representativeness. Additionally, it facilitates the extraction of specific frames for analysis. This video capture methodology, instead of isolated photos, has been widely recommended in the literature and has been used by authors such as Hansen et al. (2018), Wu et al. (2021), and Qiao et al. (2023).


a)

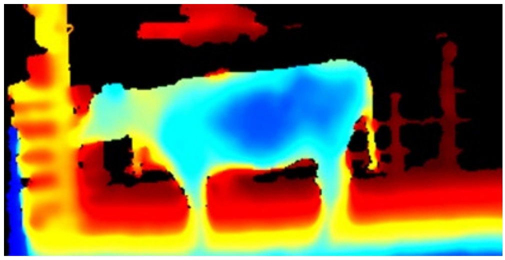

b)

Figure 3. Image capture: a) RGB image; b) depth image.

In addition to the 2D images captured by the Intel RealSense Viewer® software, it also allows for the acquisition of 3D images in the form of meshes and point clouds (Fig. 4). In this study, these 3D images played a central role, being used for the measurement of the CC of the cattle from lateral captures.

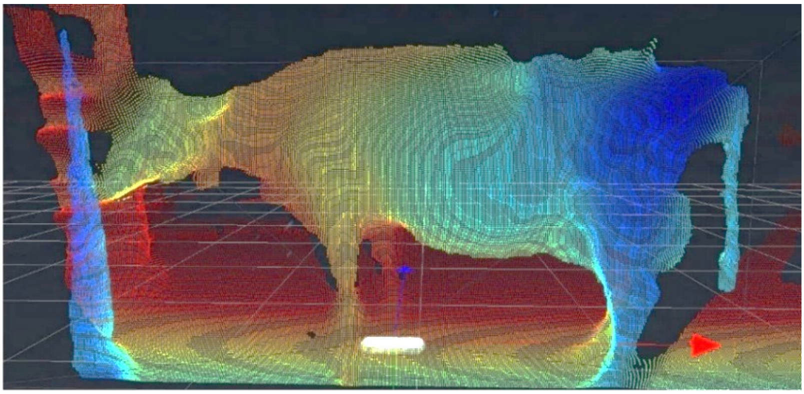


Figure 4. Representation of a 3D point cloud image in Intel RealSense Viewer® software.

The 3D images underwent preprocessing in the CloudCompare® software (version 2.13.1) to exclusively segment the region of interest, corresponding to the animal's lateral side, removing the background and other unwanted parts of the image (Fig. 5). Segmentation was performed manually in CloudCompare using the 'Segment' tool to outline the animal's side by marking multiple points, forming straight lines that define the region of interest. At this stage, parts such as the head and tail may or may not be removed, depending on the need, to facilitate the segmentation of the thoracic region. This decision is

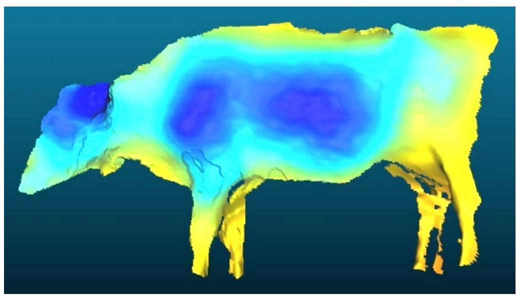


Figure 5. Segmented image in CloudCompare® software.

possible since the postural standardization had already been considered during frame selection. After segmentation, the isolated region was extracted as a new entity and, when necessary, refined with the help of the 'Cross Section' tool, which allows cutting residual elements based on section planes. It is important to note that the original mesh generated by the camera was kept unchanged in terms of resolution or retopology, ensuring geometric fidelity during segmentation. At the end of the process, the segmented mesh was saved in OBJ format for later analysis in the MeshInspector software (version 2.4.7.79). This process ensured greater precision and focus on the area required for the analysis.

From the segmentation, the resulting 3D meshes were imported into the MeshInspector® software, where the geodesic measurement of the CC was performed (Fig. 6). This perimeter was identified on the visible lateral portion of the 3D image and corresponds to approximately half of the total CC. In MeshInspector, the segmented mesh was loaded in the format exported from CloudCompare and initially visualized in TopView mode, which automatically positions the animal according to its movement on the horizontal plane, allowing for a clear observation of the lateral region. To perform the geodesic measurement, the Geodesic Path tool was used, accessed from the Inspect tab. To ensure greater accuracy in selecting the start and end points of the measurement, the mesh was slightly rotated along the vertical axis to clearly identify the deepest point of the lateral curvature of the thorax at each end of the 3D image. The measurement was made with only two points, positioned similarly to the traditional tape measure method: just behind the front legs and at the top of the lateral projection, simulating the thoracic arch (Fig. 6). The tool then automatically calculated the geodesic contour over the mesh surface between these two points, providing a value corresponding to approximately half of the CC. The unit was set to meters, and the values were later converted to centimeters to ensure compatibility with the physical data obtained in the field.

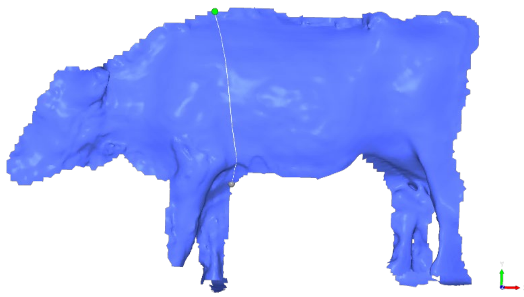
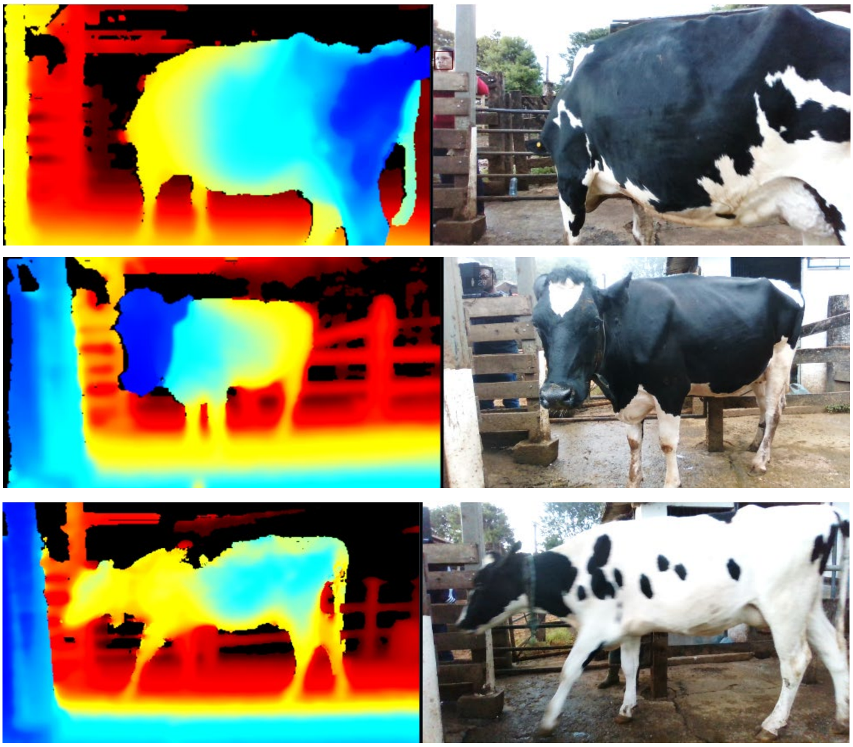


Figure 6. Geodetic measurement of CC in MeshInspector® software.

To enable comparisons with physically measured values, the obtained value was adjusted by multiplying by 2, creating an estimate of the complete CC. This approach combined advanced technologies and image processing techniques to facilitate a more detailed and robust analysis of the morphological characteristics of the cattle.

To ensure the reliability of the estimates, a careful selection of images used in the analysis was performed. Only frames with proper body posture and image quality were considered, excluding those with misalignment of the body axis (Fig. 7, a), the head turned laterally (Fig. 7, b), or visual distortions caused by light reflection on bright coat areas, which affected contour definition (Fig. 7, c). Only frames in which the animals' front legs were approximately parallel and their heads were facing forward - simulating the conventional posture adopted in manual tape measurements - were retained. Since an individual video was recorded for each animal during the journey between the milking area and the scale, several frames were captured, allowing for the selection of the most appropriate one for analysis according to the established criteria. Thus, although only a single camera positioned laterally was used, the careful selection of frames acted as a practical control for postural standardization, contributing to the consistency of the measurements obtained.



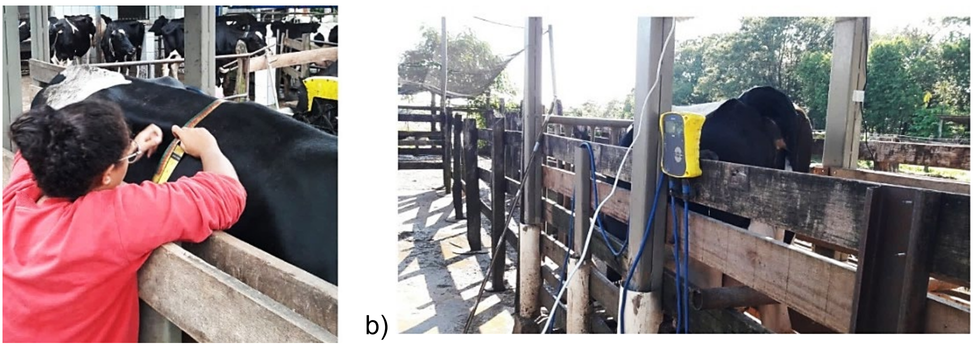
a)
b)
c)

Figure 7. Examples of images rejected for CC measurement, organized in pairs with RGB view (right) and Depth view (left): a) misalignment of the body axis; b) head turned laterally; c) visual distortion caused by light reflection.

Although estimating CC by duplicating the lateral measurement implies an assumption of bilateral symmetry, this approach was applied based on the visual quality of the selected images, aiming to minimize distortions associated with anatomical asymmetries or physiological variations, such as rumen filling, for example. Similarly, Guo et al. (2019) developed a posture normalization method based on bilateral symmetry to standardize animal poses in 3D point clouds, emphasizing that, while promising, this approach requires a series of assumptions regarding animal morphology and posture, such as standing on flat ground and presenting symmetrical body shapes. Nonetheless, it is acknowledged that, under field conditions, it is challenging to obtain situations perfectly aligned with the assumption of bilateral symmetry, given the natural variations in posture, conformation, and animal movement. Precisely for this reason lies the real challenge and contribution of this type of approach: to develop robust models capable of accurately predicting body mass even in the face of imperfections inherent to the production environment.

Additionally, it was observed that cows with predominantly white coats were more susceptible to visual distortions caused by the natural lighting of the environment. The high light reflection on these lighter regions resulted, in some cases, in the loss of definition of body contours in the images. This type of visual interference, associated with light variation, has already been reported in the literature as a factor that compromises image quality in production environments (Ramesh et al., 2023), although not directly related to coat color. In the present study, however, this effect was more evident in light-colored animals, which led to the exclusion of the affected frames to ensure the consistency of the measurements. Meng et al. (2025), in a systematic review on animal biometrics based on computer vision, highlight that variations in lighting conditions and capture angles remain critical factors for model accuracy, even with the use of 3D cameras. This reinforces the idea that, although technology is advancing, model robustness still needs to address the natural imperfections of the production environment.

After the images of each cow were collected, the animals were weighed and measured while contained on the scale. During this process, in addition to obtaining the BM data in kilograms directly from the scale, CC measurements were manually taken in centimeters using a measuring tape. In order to maintain the normal workflow on the farm and avoid delays during the milking and weighing routine, each measurement was performed only once per animal, always by the same trained evaluator, following a standardized protocol. This approach aimed to ensure the consistency of the reference measurements, even without formal repetition, reflecting common practice in dairy production systems and allowing for a proper comparison with the automated approach proposed in the present study. The measurements taken with measuring tapes, providing values in centimeters, can be used as input data for predictive equations, widely employed in estimating BM, as seen in studies like Pereira et al. (2021), where the CC predictor was included in their predictive equation for dairy cattle weight.



a) b)

Figure 8. Measurements: a) CC measurement; b) BM measurement.

These BM and CC values were recorded as fundamental references for the validation and subsequent analyses performed on the captured images, ensuring greater accuracy and reliability in the results obtained from the computer vision approaches. Fig. 8 illustrates the methods of collecting CC measurements with the measuring tape and BM via the digital scale.

RESULTS AND DISCUSSION

The data presented in Table 1 include the minimum, mean, and maximum values of the body masses and perimeters analyzed. These values summarize the observed ranges of the studied variables, serving as a basis for sample characterization and subsequent analyses.

Table 1. Descriptive Statistics of BM and Measured CC in Dairy Cattle

Variable	Minimum	Mean	Maximum	Standard Deviation (%)
Body Mass (kg)	420	613.31	855	-
CC Physically measured[1] (cm)	184	209.23	241	4.44
CC measured in the images[2] (cm)	89.30	103.01	120.30	4.56
Adjusted CC[3] (cm)	178.60	206.03	240.60	4.56

[1] Chest Circumference measured in the field; [2] Chest Circumference measured in the images; [3] Chest Circumference adjusted by multiplication by 2.

The minimum and maximum ranges of the analyzed variables show a wide distribution, varying from 420 kg to 855 kg, reflecting the diversity of the morphological characteristics of the evaluated cows. The consistency observed between the adjusted CC values obtained from the images and the physically measured values suggests that the adopted adjustment technique (multiplication by 2) was effective in approximating the values to the actual measurements.

When comparing the physically measured CC with the adjusted CC obtained from 3D images, an average difference of only 3.2 cm is observed, indicating that the adjustment technique applied to the 3D images can be a viable alternative for estimating CC without the need for manual measurements. The standard deviation in percentage highlights the uniformity of the measurements relative to the calculated means, showing similar variations between the CC measurement methods. This stability is a positive indicator of data reliability for both physical measurements and image-based estimates.

Studies have demonstrated a strong correlation between CC and BM in cattle, reinforcing its use as a reliable predictor. Lukuyu et al. (2016), for example, identified a correlation of ($r = 0.84$) between CC and BM in crossbred cattle, working with a weight range of 102 to 433 kg. Later, Franco et al. (2017) confirmed the strong association between CC and BM when studying Holstein and crossbred heifers, finding an even higher correlation ($r = 0.94$) within a narrower weight range of 212 to 345 kg. More recently, Weber et al. (2020) analyzed Girolando cattle and reinforced these findings, reporting a correlation of ($r = 0.88$) for a weight range of 360 to 596 kg. These studies support the relevance of CC as a robust and widely applicable metric for weight estimation across different contexts and morphological conditions.

The results of this study reinforce the strong relationship between CC and BM in cattle. The Pearson correlation found between BM and the CC measured in the field ($r = 0.90$) falls into the 'very high' correlation category according to Mukaka (2012), indicating the strong accuracy of this traditional weight assessment method. On the other hand, the CC estimated from processed lateral images showed a slightly lower correlation ($r = 0.85$), classified as 'high' by the same reference. This difference may be attributed to the estimation method for the complete circumference, which involved doubling the value measured in the lateral image, as well as limitations associated with geodesic measurement in 3D meshes, such as possible segmentation inaccuracies or distortions in 3D capture. Nevertheless, the use of processed images proved to be a promising and non-invasive approach, capable of providing consistent results with potential for practical applications in BM prediction in cattle.

Based on the strong correlation observed between CC and BM, BM was estimated using a simple linear regression model. For this purpose, the data were split into 80% for training and 20% for testing, ensuring that the data used in the testing phase were not included in the model training process. During training, 10-fold cross-validation was applied to assess the model's stability and generalization capacity. Additionally, a residual analysis was performed to evaluate the fit and identify potential error patterns. Fig. 9 shows the results of the trained models, and Fig. 10 presents the residuals.

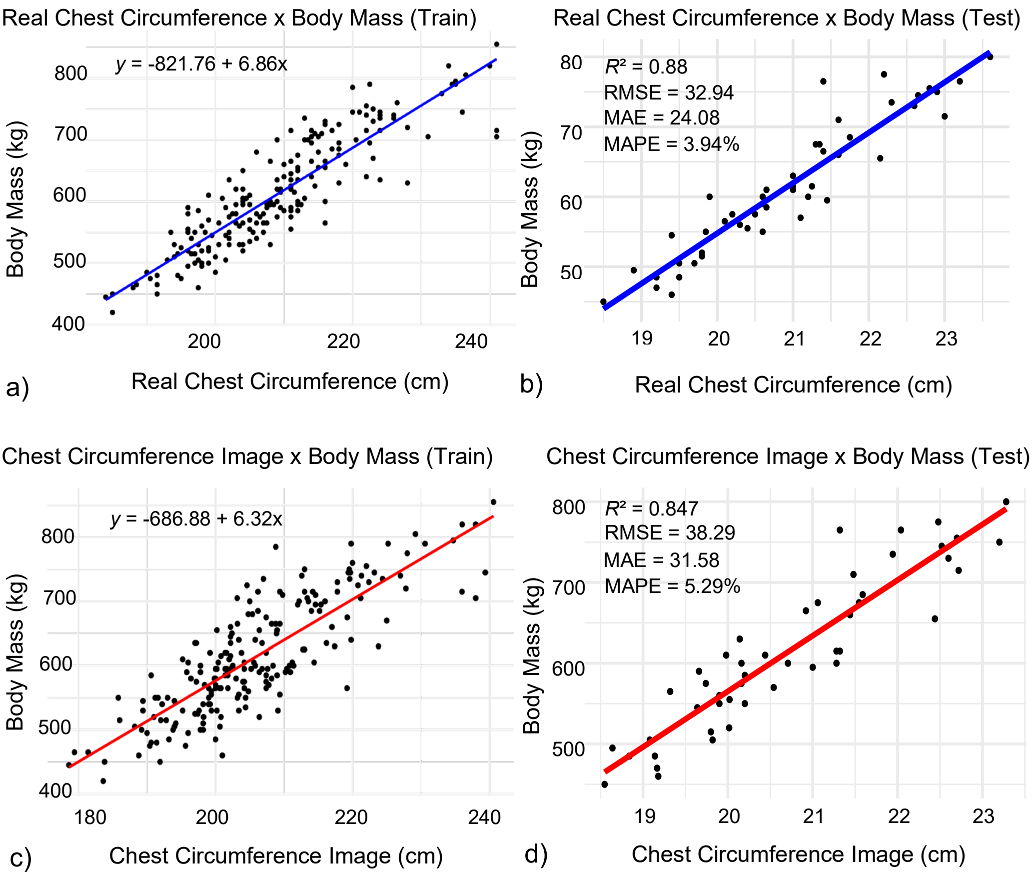


Figure 9. Regression plots: a) training data of chest circumference (CC) measured in the field and body mass (BM); b) test data of CC measured in the field and BM; c) training data of CC measured from images and BM; d) test data of CC measured from images and BM.

The residual analysis of the models, presented in Fig. 10, provides an initial assessment of how the predictions behave in relation to the actual body mass values. It can be observed that in both cases - the model using chest circumference measured in the field and the model using image-based estimates - the residuals are reasonably symmetrically distributed around the zero line, suggesting no evident systematic bias. However, some residual values with magnitudes close to or exceeding ± 50 stand out. These points may be considered outliers and warrant further investigation, as they could be related to specific morphological characteristics of the animals or to limitations in the predictor variable estimation. Still, they do not indicate a recurring pattern. Additionally, the distribution of residuals across the range of predicted values shows an approximately constant error variance - a feature known as homoscedasticity - which is a positive indicator for the validity of the applied simple linear regression models. This preliminary visualization of the residuals thus helps contextualize the results that will be presented next in terms of error metrics and predictive accuracy.

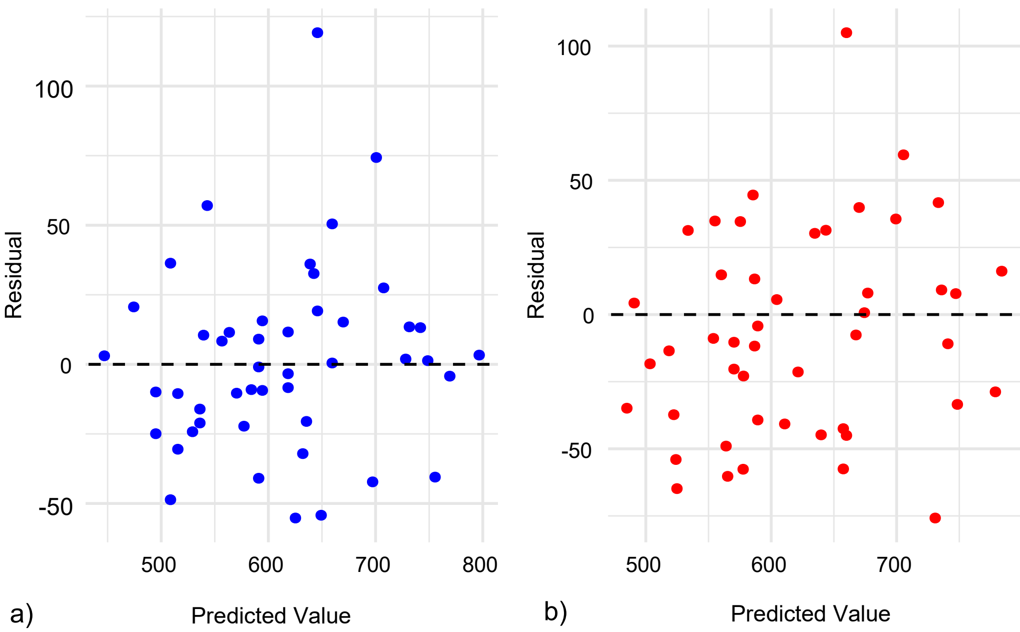


Figure 10. Distribution of residuals from simple linear regression models for predicting BM of cattle: a) residuals from the model using field-measured CC; b) residuals from the model using image-based CC.

Continuing the analysis, the results presented in Fig. 9 show that CC measured in the field exhibited a strong correlation with BM, serving as an efficient predictor, with a coefficient of determination (R^2) of 0.88 and a Mean Absolute Error (MAE) of 24.08 kg. This R^2 value indicates that the model explains 88% of the variation in the BM of the cattle, reflecting the reliability of CC as a predictor of BM. However, the MAE of 24.08 kg suggests that, despite the strong correlation, the estimate still has a considerable error, which may be deemed acceptable depending on the application context, such as in large herds where absolute precision may be of secondary importance.

Kashoma et al. (2011) investigated the relationship between CC and BM in Tanzania Shorthorn Zebu (TSHZ) cattle, with weights ranging from 170 to 390 kg. The study reported a coefficient of determination of $R^2 = 0.88$, demonstrating a strong linear relationship between these variables. Additionally, the authors highlighted that factors such as sex could influence this relationship, with males and females exhibiting differences in the association between CC and BM. Similarly, Franco et al. (2017) evaluated different equations based on CC to predict BM in cattle, with R^2 values ranging from 0.75 to 0.90, as presented in their models. This variation illustrates how different ap*proaches and adjustments can impact model accuracy, with the best performance* ($R^2 = 0.90$) achieved using a simple equation that considers only CC, with a coefficient of variation (CV) of 5.9%. These findings reinforce the robustness of CC as a predictive variable while also indicating that adjustments specific to herd characteristics and data collection methods can influence the results.

In contrast to the field measurements, which showed high accuracy, the CC estimated from lateral images exhibited slightly lower performance, with an R^2 of 0.847 and a MAE of 31.58 kg. Despite the slight reduction in precision, the correlation obtained is still considered strong, indicating that the image-based approach is capable of consistently capturing the relationship between CC and BM. The observed difference in MAE may be related to factors such as the morphological variability of the animals, possible limitations in image capture, or the lack of control over environmental conditions at the time of acquisition. Nevertheless, the use of lateral images represents a practical, non-invasive alternative with good performance for estimating BM, especially useful in scenarios with limited animal access or in large-scale herds where conventional measurement methods are less feasible. The results reinforce the potential of computer vision applied to precision livestock farming, even when compared to traditional methods.

The regressions performed demonstrate that as the CC increases, there is a proportional increase in BM, as evidenced by various studies, including those by Gomes et al. (2016), Weber et al. (2020), and several others. This behavior occurs because the CC is a measure directly related to the animal's thoracic volume, which reflects not only the overall body size but also the capacity to store internal organs, fat, and muscle mass (Heinrichs et al., 1992). In larger animals, the increase in CC is associated with a more advanced development of the body structure and greater deposition of lean mass and/or fat, which are the main determinants of live weight (Bene et al., 2007). Therefore, CC serves as a practical and accessible indicator for estimating BM, showing a strong correlation with this variable in various studies.

Complementing the evaluation of the predictive performance of the models, the root mean square error (RMSE) was 32.94 kg for the model using field-measured CC, and 38.29 kg for the model based on image-derived estimates. The mean absolute percentage error (MAPE) values were 3.94% and 5.29%, respectively. These results indicate that both models demonstrated good accuracy, with slightly better performance for the model using physical measurements, although the image-based approach also showed relatively low error, considering its practical application context.

When compared to some studies, the MAPE values obtained in this work demonstrate competitive performance. Dang et al. (2022) used a set of ten manually collected body measurements to estimate the live weight of Hanwoo cattle using different machine learning algorithms. Among the models tested, LightGBM achieved the best performance, with an RMSE of 24.75 kg and a MAPE of 4.72%. Although this absolute error is lower than the RMSE obtained in the present study (32.94 kg and 38.29 kg), it is important to highlight that Dang et al.'s (2022) models used a multivariate set of predictors, whereas the present study used only CC as the independent variable.

Even so, the model using physical measurements achieved a lower MAPE (3.94%), demonstrating the strong predictive power of this single variable and its potential for use in simpler and more practical models for field application.

In a more recent study, Peng et al. (2024) explored the use of lateral depth images combined with pose estimation algorithms to estimate cows CC and subsequently predict BM. The model proposed by the authors achieved a mean percentage error of 4.43%, an intermediate value between those obtained in the present study by the models using real chest circumference (3.94%) and estimated 3D image-based circumference (5.29%). Although Peng et al.'s (2024) methodology represents an advance in terms of automation and reduction of direct measurements, the results presented here suggest that 3D image-based approaches with lateral segmentation are also capable of achieving similar performance, even with relatively simpler processing and fewer input variables.

Based on the reviewed research, it is possible to observe that including other variables in the models, such as age, sex, and specific characteristics of the cattle, or even using different techniques, can contribute to greater accuracy in predicting body mass. However, the method used in this study, which integrates direct measurements and advanced computer vision techniques, has proven to be efficient and innovative, allowing for precise and automated analysis, with potential for practical application in dairy herds of different configurations. This approach represents a significant advancement over traditional methods, proving to be a robust tool to assist in management and decision-making.

CONCLUSIONS

Based on the results obtained, it can be concluded that chest circumference is a reliable predictor of body mass in cattle, both through direct measurements and estimates from three-dimensional images. Although the estimation via images showed a slight reduction in accuracy compared to direct measurements, it presents itself as a viable and non-invasive alternative, especially for large or hard-to-reach herds. The imaging technique, despite being subject to limitations such as uncertainties in geodesic measurements and adjustments by multiplication, offers a practical solution for remote BM monitoring. With the advancement of technologies and the expansion of the database, the accuracy of the models is expected to improve, broadening the applications of these techniques in precision agriculture and efficient herd management.

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Carbon and nitrogen accumulation by agricultural crop residue under three cropping systems

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Abstract. Agricultural crops produce different biomass during their growth, including varying amounts of residue which accumulate a significant amount of carbon (C) and nitrogen (N). Assimilation capacity depends largely on species, variety and growing condition. Carbon accumulation in soil contributes to both - the agricultural production and maintenance of environmental quality reducing atmospheric C and greenhouse gas emissions. In this study, the amount of plant residue left on the field by above-ground and below-ground residue and the amount of C and N accumulated in them in three different cropping systems: organic (Bio); integrated with a low input of N fertiliser (Int-low-N) and; integrated with a high input of N fertiliser (Int-high-N) were evaluated. The most commonly grown cereal crops in Latvia were tested: winter wheat (WW); summer wheat (SW); winter rye (WR); winter triticale (WT); summer barley (SB); summer oat (SO); and buckwheat (BW) as pseudo-cereal crop. The highest biomass of dry matter of total harvest residue in all cropping systems was recorded in WR: 853.3 ± 40.76 g m^{-2}; 1,482.0 ± 105.06 g m^{-2}; 1,628.3 ± 115.49 g m^{-2} - in Bio; Int-low-N; Int-high-N cropping systems, respectively. The highest amount of carbon (g C m^{-2}) using organic cropping system was accumulated by residue of: WR (268.6 ± 28.68), BW (239.4 ± 10.50) and WW (234.5 ± 27.41). The highest amount of carbon (g C m^{-2}) using integrated cropping system was accumulated by residue of: WR - 473.8 ± 64.9; 496.6 ± 62.54 and WT - 458.2 ± 32.57; 521.1 ± 46.26 in Int-low-N and Int-high-N, respectively. Higher proportion of root biomass cereals formed using organic cropping system.

Key words: above-ground and below-ground residue, cereal crops, integrated cropping system, organic cropping system.

INTRODUCTION

Increase of carbon and nitrogen storages can improve soil quality and reduce of atmospheric carbon dioxide (CO_2) and nitric oxide (N_2O) concentration in the atmosphere which results in a decrease the greenhouse effect (Nath et al., 2017; Lal et al., 2021). Carbon management in agriculture could be a very efficient measure to mitigate the increased concentration of CO_2 in the atmosphere maximizing the uptake and promoting its storage in soil organic matter (Tariq et al., 2023). Soils represent a massive stock of terrestrial organic carbon (C) and act both as a buffer against atmospheric CO_2 increase and as a potential sink for additional C depending on the balance between photosynthesis, the respiration of decomposer organisms, and stabilization of C in soil (Rodrigues et al., 2023).

There is a great potential to increase carbon sequestration in agricultural soils using different management practices - crop rotation, minimal soil disturbance, crop residue incorporation could be key elements for the success of conservation agriculture (Giller et al., 2015). A range of agricultural measures, including use of purposeful crop rotation in different farming systems can significantly affect the capture of atmospheric carbon and store it within the soil (Avasiloaiei et al., 2023).

Given the significant role of soil as a carbon sink, preserving and increasing soil organic carbon (SOC) stocks are current priorities. The European Commission has suggested increasing focus on carbon farming initiatives to contribute to the land carbon sink that is required to meet the 2030 climate target of the net removal of 310 Mt CO_2 from the atmosphere (European Commission, 2021). Moreover, there has set the ambitious goal of increasing soil carbon stocks by 0.4% a year as a way to offset the global emissions of GHG and mitigate climate change (Minasny et al., 2017; Latorre et al., 2024).

Carbon input into the soil using various methods, including retention of C bound in plants is an essential prerequisite for organic matter conservation in the soil. Carbon supply is usually related to the build-up of soil fertility, which in turn allows for a reduction of external inputs, such as synthetic fertilizers and pesticides. Crop residue incorporation to the soil is an essential strategy to improve soil quality and crop productivity in order to attain sustainable development goals (Hamelin et al., 2019). Stubble retention that increase residue inputs typically facilitate SOC storage. Agricultural crops having large root system and high biomass translates to better weed management, soil moisture conservation, and fertility improvement, in addition to protection of soil from erosion (Murungu et al., 2011).

The appropriate management of soil organic matter (SOM) in an agricultural production system is an essential issue in reducing the greenhouse gas (GHG) emmissions. The decomposition of organic matter releases C and contributes to the increase in GHG emissions. Therefore, it is important to ensure a continuous inflow of organic matter to the soil. A good solution is the incorporation of various plant material, including harvest residues, root mass and organic fertilizer into the soil. This could help to neutralize the effects of SOM degradation, which raises concerns about C loss in the form of CO_2 emissions into the atmosphere (Lal, 2004; Navarro-Pedreno, 2021).

Leaving as large as possible amounts of post-harvest residue on the soil surface can contribute to the reducing GHG emissions directly - through the accumulation of organic C and indirectly - reducing fuel consumption and mineral fertilizer production volumes

(Hussain et al., 2022). It is estimated that 15% of photosynthetically fixed carbon is allocated into the soil via plant roots (Farrar et al., 2003). Incorporating crop residue into the soil enhances nutrient cycling, improves soil structure and promotes plant growth through their contribution to the SOC pools (Liu et al., 2014; Poeplau et al., 2015). Returning crop residue to soil using proper methods is beneficial to soil health, promoting crop productivity and sustainable agriculture (Fu et al., 2021).

Using sustainable agricultural methods, such as organic farming, can contribute in increase of organic carbon sequestration in the long term. At the same time it can reduce GHG emissions from the agricultural sector due to the fact that this system does not use synthetic nitrogen fertilizers. When used in combination with other environmentally friendly farming practices, this can lead to significant reductions in greenhouse gas emissions (Holka et al., 2022). Some studies show that organic farming practices increased SOM content by 1.90 t C per ha per year, while conventional farming practices decreased it by 1.24 t C per ha per year (Stalenga & Kawalec, 2007). Other studies also agree with the above mentioned, confirming the trend of higher SOM using organic farming practice (Brock et al., 2012).

Carbon input into the soil by plant root system is one of the most important variables driving soil C dynamics in agroecosystems and ensuring C sequestration in the long term (Kell et al., 2017). Below ground carbon (BGC) inputs reside in soil considerably longer than C derived from above-ground harvest residue and organic soil amendments (Rasse et al., 2005). As it is inherently difficult to measure BGC input in the field, it is usually estimated from yield in order to supply soil C models with input data. Several findings (Bolinder et al., 2007; Kell at al., 2017; Hirte et al., 2018) imply that yield-independent values provide closer estimates for BGC inputs to soil of cereals in different farming systems than yield-based functions. Subsequently they conclude that fertilization has only little potential to alter absolute amounts of BGC inputs to deep soil in order to sequester C in the long term. Different factors including cropping system, fertilization rate, species etc. might have a considerable impact on plant C allocation and uptake capacity. There is no definite answer, whether C inputs with below-ground residue can be reliable estimated from yield. In contrast to the concept of allometry, recent findings suggest that BGC inputs are not proportional to net primary productivity in agroecosystems and are rather a function of year, species, and farming system (Taghizadeh-Toosi et al., 2016; Hu et al., 2018).

The objectives of our studies were to quantify amount of above-ground and below-ground residue and accumulated carbon (C) and nitrogen (N) for most commonly grown cereal crops in Latvia: winter and summer wheat; winter rye; winter triticale; summer barley; summer oat; and, buckwheat using three farming systems: organic (Bio); integrated with a low input of N fertiliser (Int-low-N) and; integrated with a high input of N fertiliser (Int-high-N).

MATERIALS AND METHODS

Experimental design and background

In the field experiment most commonly grown cereals in Latvia were included - winter crops: wheat (WW), rye (WR), triticale (WT); and summer crops: wheat (SW), barley (SB), oat (SO), buckwheat (BW). Each crop in the field trials was represented by two biologically/morphologically distinct varieties (V1 and V2) which were grown using a respectable integrated (Int) and organic (Bio) farming practices. Since wheat and barley are more intensively cultivated species, the most suitable and most frequently used varieties were chosen for each cropping system. The list of all crop varieties and their brief characteristic is summarized in the Table 1.

Table 1. A brief description of the varieties included in the trial and information on their use in different cropping systems and seasons

Crop	Variety	Earliness	Stem length	Cropping system		
				2018	2019	2020
Winter wheat	Fredis	early	short stem	Int	Int	Int
	Brencis	semi early	long stem	-	Int	Int
	Edvins	early	long stem	Bio	Bio	Bio
	Talsis	semi early	long stem	-	Bio	Bio
Winter rye	Su Nasri (hybrid)	early	short stem	-	Int, Bio	Int, Bio
	Kaupo	semi early	long stem	-	Int, Bio	Int, Bio
Winter triticale	Ruja	semi late	long stem	-	Int, Bio	Int
	Ramico	semi early	short stem	-	Int, Bio	Int
Spring wheat	Taifun	semi late	short stem	Int	Int	Int
	Uffo	semi early	long stem	Int, Bio	Int, Bio	Int, Bio
	Robijs	semi late	long stem	Bio	Bio	Bio
Spring barley	Ansis	semi late	short stem	Int	Int	Int
	Kristaps	semi early	long stem	Int	Int	Int
	Rasa	early	long stem	Bio	Bio	Bio
	Jumara	semi late	long stem	Bio	Bio	Bio
Spring oat	Laima	semi early	long stem	Int, Bio	Int, Bio	Int, Bio
	Suymphony	semi late	long stem	Int, Bio	Int, Bio	Int, Bio
Buckwheat	Aiva	semi late	long stem	Int, Bio	Int, Bio	Int, Bio
	Nojas	early	long stem	Int, Bio	Int, Bio	Int, Bio

The field trials were carried out in the Stende Research Centre of the Institute of Agroresources and Economics (57.1867N, 22.5477E) in the fields of stationary plant rotation corresponding to the integrated and organic farming system. The soil type in both plant rotations was *Eutric Abeluvisols* (WRB), the soil texture - light loam (Int and Bio-1) and clay sand (Bio-). Characteristics of the experimental fields are summarized in the Tables 2, 3.

Table 2. The soil characteristic and pre-crops in integrated experimental fields

Soil indicators	2018		2019		2020	
	winter crops	spring crops	winter crops	spring crops	winter crops	spring crops
pH KCl	5.6–5.8	5.1–5.8	5.9–6.3	5.0–5.6	6.3–6.7	5.3–5.6
Organic matter, %	1.8–2.0	1.8–2.0	1.5–2.1	1.8–2.0	3.3–3.4	1.9–2.3
K_2O mg kg^{-1}	200–218	189–204	144–165	201–232	158–160	218–240
P_2O_5 mg kg^{-1}	161–192	160–206	147–150	150–186	122–144	161–193
Pre-crop	winter rape	field bean	green manure	potatoes	winter rape	potatoes

Table 3. The soil characteristic and pre-crops in organic cropping experimental fields

Soil indicators	2018 winter crops	2018 spring crops	2019 winter crops	2019 spring crops	2020 winter crops	2020 spring crops
Organic field Bio-1						
pH KCl	6.8	6.4	6.8	6.4	5.9	6.0
Organic matter, %	2.3	2.7	1.9	2.8	3.2	1.9
K_2O mg kg^{-1}	90.8	127	114	127	122	108
P_2O_5 mg kg^{-1}	183	206	199	206	201	171
Pre-crop	green manure	winter wheat	spring barley	spring oat	potatoes	winter wheat
Organic field Bio-2						
pH KCl	5.8	6.1	6.4	6.4	-	6.7
Organic matter, %	3.8	4.9	2.5	4.9	-	4.5
K_2O mg kg^{-1}	135	42	132	52	-	75
P_2O_5 mg kg^{-1}	83	19	188	39	-	39
Pre-crop	green manure	green manure	potatoes	green manure	-	buckwheat

In integrated farming practice, studies were implemented by observing two levels of cultivation intensity, which differ in the amount of nitrogen fertilizer used: Int-low-N (the lowest fertilizer rate) and Int-high-N (the highest fertilizer rate) and correspond to the most commonly used N fertilizer rate for a specific species in farm practice. In an integrated farming system, complex mineral fertilizer was incorporated into the soil before sowing: NPK (10-26-26) 330 kg ha^{-1} for winter crops; NPK (8-20-20) 350 kg ha^{-1} for summer crops. These mineral fertilization rates for each field plant species are listed in the Table 4.

Table 4. The nitrogen fertilizer rates for different crops in an integrated farming system

Cereals	Fertilization rate in spring (N, kg ha^{-1} in pure matter)	
	Int-low-N	Int-high-N
Winter wheat (WW)	75*	135*
Winter rye (WR)	75*	115*
Winter triticale (WT)	75*	135*
Spring wheat (SW)	100	140
Spring barley (SB)	100	140
Spring oat (SO)	80	100
Buckwheat (BW)	80	100

* before winter crop sowing, soil was fertilized with basic complex (NPK) mineral fertilizer, including 33 N kg ha^{-1} in pure matter.

In organic farming practice, experiments were conducted in two fields with different soil fertility indicators (Bio-1 and Bio-2). In organic farming plant rotations, nutrients were provided by growing green manure plants and incorporating the residue of the previous crop into the soil (straw, roots, etc.).

The soil cultivation was carried out by plowing in the fall to a depth of 15 to 18 cm. Before sowing the soil was leveled using a harrow and cultivated to a depth of 5 cm. Sowing was done for each species in optimal sowing terms, observing the distance between rows of 12.5 cm. Sowing rate was 450–500 germinating seeds per m^2 for cereal species; 220 germinating seeds per m^2 for buckwheat. In the field experiments, each research variant was arranged in a 20 m^2 plot area in four replicates. Research options were arranged on the field in blocks. Plant biomass samples were collected at the stage of Zadoks Growth Stage

GS84–89. The grain from all plot was harvested with a small-sized grain harvester Wintersteiger Delta at the stage GS95–99.

Collection and analysis of samples

The cereal plant biomass samples were taken from 0.125 m^2 area in two locations in each plot. For below-ground (BG) residue sampling, the 0.0–0.2 m soil profile was taken using the same accounting area used for the above-ground (AG) residue. Roots were rinsed on a sieve with a mesh size of 1.0×1.0 mm. Below-ground and above-ground residue samples were air-dried and weighed separately using a laboratory scale (with an accuracy of 0.01 g). The dry matter (DM) of each sample was determined according to the standard ISO 6496:1999 at the Laboratory of Cereal Technology and Agricultural Chemistry of the Institute of Agricultural Resources and Economics. To determine the carbon content in biomass, the following methods according to the LVS ISO standards LVS ISO 10694:2006 and LVS ISO 13878:1998 were used: total carbon (C) and total nitrogen (N) by an elemental analyser (dry combustion) vario EL cube.

Description of the meteorological conditions

In all three growing seasons when field experiments were conducted, the monthly air temperatures exceeded the long-term averages. Separate short periods of extreme drought and heat were also been observed in all seasons (Fig. 1).

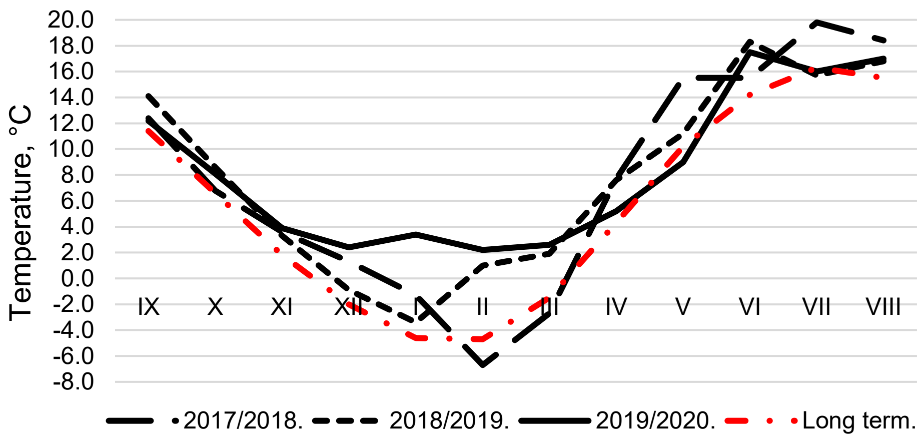

Figure 1. Average air temperatures °C (2018–2020) at Stende RC compared to the long-term averages.

During the winter period, the daily average air temperatures were favourable for wintering of wheat, rye and triticale. In April, when plant vegetation recovered, the average air temperatures in all trial years were higher than that of long-term averages. This contributed to more rapid plant development.

The spring of 2018 turned out to be very dry with only 14 mm of precipitation in May and the first two ten-day periods of June, and air temperature at that time was higher than the long-term average. Such conditions were not favourable for the optimal development of spring crops and significantly affected the production of plant biomass.

Precipitation in July and August only partially compensated the lack of moisture at the beginning of the vegetation season.

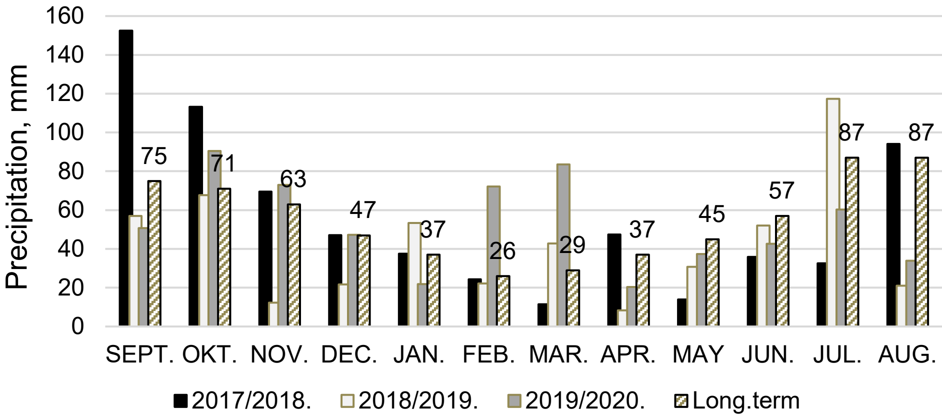

Figure 2. The amount of precipitation by month (2018–2020) at Stende RC compared to the long-term averages.

In July of 2019 and 2020, monthly air temperatures were close to long-term averages (Fig. 1). The highest amount of precipitation in the years of the experiment was observed in late July and August (Fig. 2). This is consistent with long-term observations. Part of the precipitation during this period came with heavy rains and thunderstorms, such precipitation quickly flows away from the field to water bodies (rivers, ditches), does not accumulate in the soil, and plants can use it only partially. Winter crops usually reach maturity in the first days of August, the amount of precipitation received until the last ten days of July is crucial for increasing their biomass whereas for summer crops it is the amount of precipitation until the first ten days of August.

Statistical analysis

The experimental data were statistically processed using descriptive statistics methods and Pearson correlation by Microsoft Excel and IBM SPSS Statistics for Windows. The normal distribution of the data was checked using Kurtosis and Skewness values. Regression and analysis of variance (ANOVA) were performed using R Studio for Windows (RStudio, PBC). The statistical indicators for regression and ANOVA are the *p*-value for the model parameters, and the R2 for the usefulness of the regression model. The entire database was used for regression ANOVA. To determine significant differences, a t-Test: Two-Sample Assuming Unequal Variances was used. Pairs were compared with each other, i.e.: Bio (a) and Int-low-N (b) cropping system; Int-low-N (b) and Int-high-N (c) cropping system; Bio (a) and Int-high-N (c) cropping system.

RESULTS AND DISCUSSION

Research data show that cereal harvest residue varied significantly with farming system and cereal species. Significant differences in the amount of above-ground (AG) residue were found between different cropping systems. The dry matter (DM) of AG residue depending of cropping system and species ranged within: 308.68 ± 11.92 g m^{-2} (s. barley) – 682.93 ± 32.18 g m^{-2} (w. rye); 568.90 ± 24.99 g m^{-2} (s. barley) – 1,250.29 ± 86.22 g m^{-2} (w. rye); and 638.70 ± 17.76 g m^{-2} (s. wheat) – 1,386.71 ± 136.15 g m^{-2} (w. triticale) in organic cropping system (Bio); integrated with low N input (Int-low-N) and; integrated with high N input (Int-high-N), respectively (Table 5). Above-ground crop residue yields are approximately 60% of grain yield, meaning large inputs of residue carbon into soils (Gosling et al., 2017). High biomass translates to better weed management, soil moisture conservation, and fertility improvement (Murungu et al., 2011). Crop residues used as mulch are central to the success of moisture conservation, weed suppression, and SOM improvement, and as a result high soil and crop productivity (Hatfield, 2001; Hamelin et al., 2019).

Table 5. Above-ground residue (DM, g m^{-2}) of different cereals in different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	525.99 ± 35.30[a]	776.19 ± 25.52[b]	867.09 ± 25.81[c]
S. wheat	368.99 ± 18.40[a]	589.40 ± 17.67[b]	638.70 ± 17.76[c]
W. rye	682.93 ± 32.18[a]	1,250.29 ± 86.22[b]	1,380.88 ± 93.95[c]
W. triticale	454.94 ± 32.89[a]	1,231.92 ± 103.69[b]	1,386.71 ± 136.15[c]
S. barley	308.68 ± 11.92[a]	568.90 ± 24.99[b]	643.08 ± 23.82[c]
S. oat	374.09 ± 16.07[a]	688.60 ± 22.24[b]	745.87 ± 22.96[c]
Buckwheat	543.58 ± 23.24[a]	580.39 ± 32.21[a]	748.14 ± 36.34[b]

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

Also, with respect to the biomass of below-ground (BG) residue, significant differences were found both between different cropping systems and species used. The lowest amount of BG residue in all systems was produced by buckwheat. Among cropping systems, the DM of BG residue ranged within: 63.93 ± 1.81 g m^{-2} (buckwheat) – 170.36 ± 12.33 g m^{-2} (w. rye); 66.71 ± 3.78 g m^{-2} (buckwheat) – 232.41 ± 20.78 g m^{-2} (w. triticale); 84.10 ± 5.01 g m^{-2} (buckwheat) – 275.16 ± 26.16 g m^{-2} (w. triticale) in Bio system; Int-low-N and; Int-high-N input system, respectively (Table 6).

Table 6. Below-ground residue (DM, g m^{-2}) of different cereals in different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	113.36 ± 9.60[a]	143.94 ± 12.41[b]	141.63 ± 10.84[c]
S. wheat	80.00 ± 3.91[a]	123.50 ± 5.32[b]	134.26 ± 6.51[c]
W. rye	170.36 ± 12.33[a]	231.73 ± 21.65[b]	247.40 ± 24.62[b]
W. triticale	132.22 ± 10.08[a]	232.41 ± 20.78[b]	275.16 ± 26.16[c]
S. barley	78.15 ± 6.62	83.64 ± 2.13	87.59 ± 1.83
S. oat	105.28 ± 6.19[a]	141.50 ± 5.73[b]	145.76 ± 6.30[c]
Buckwheat	63.93 ± 1.81[a]	66.71 ± 3.78[a]	84.10 ± 5.01[b]

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

In our research, BG residue accounted for an average of 23% of AG residue in the Bio system (among crops it ranged within 12–29%). The differences in integrated cropping system between Int-low-N and Int-high-N input systems were insignificant: in the Int-low-N system BG residue accounted for an average 18% (11–21% depending on crop species); in the Int-high-N input system 17% (11–21% depending on crop species). Relatively higher cereal root biomass was formed in the organic cropping system (Fig. 3). This indicates to proportionally larger contribution of organic matter from the cereal BG residue even in cases when the AG residue is taken away from the field. When used together with other environmentally friendly farming practices, significant increase in soil C and reductions of GHG emissions can be achieved (Holka et al., 2022).

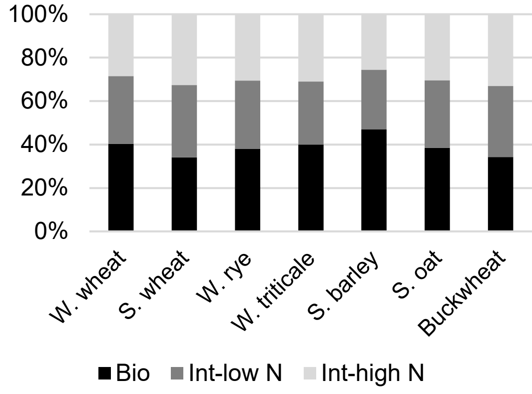

Figure 3. Proportion of root biomass (below-ground residue) in cereal crops using different farming systems.

The DM of total harvest residue (AG + BG residue) ranged within: 386.83 ± 15.53 m^{-2} (s. barley) – 853.28 ± 40.76 g m^{-2} (w. rye); 647.1 ± 35.02 g m^{-2} (buckwheat) – 1,482.02 ± 105.06 g m^{-2} (w. rye); 730.68 ± 24.92 g m^{-2} (s. barley) – 1,661.87 ± 134.95 g m^{-2} (w. triticale) in Bio; Int-low-N and; Int-high-N, respectively (Fig. 4).

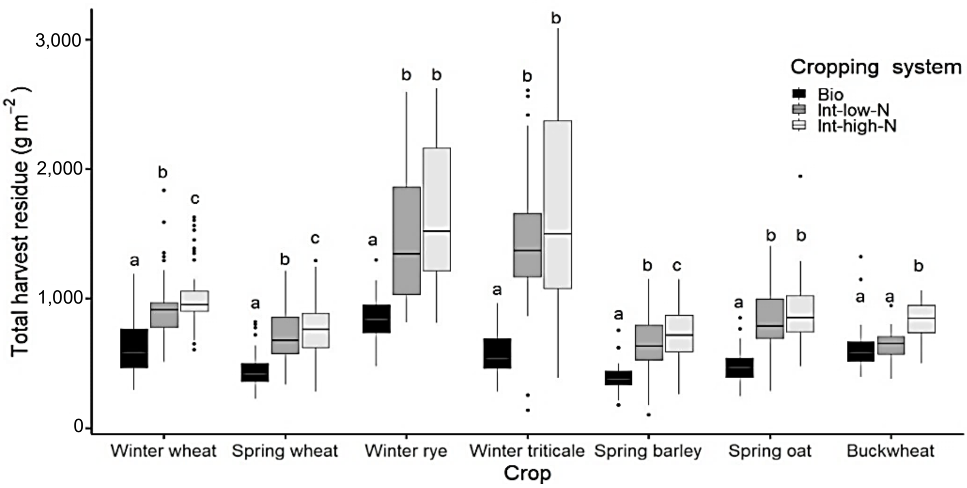

Figure 4. Total harvest residue (AG + BG residue) (DM g m^{-2}) of cereal crops in different cropping systems.

Crops that during vegetation produce large biomass and leave significand amount of crop residue in the field, such as winter rye and winter triticale, could have a beneficial effect on the growth of soil organic matter (SOM). An effective way to improve the resources of the SOM is to increase the productivity of crops, including the total amount of biomass thereby increasing the amount of crop residue (Sarkar et al., 2020).

Plants accumulate considerable amounts of C during growth. The average C content in cereal straw or AG harvest residue fluctuates around 450 g kg^{-1} C, while the C content in root mass (BG residue) is lower, it fluctuates around 370 g kg^{-1} C on average (Rancane et al., 2023). Together with the relatively lower ratio of BG residue to AG residue, the amount of accumulated C in BG residue was lower, but it still makes a significant contribution to both soil quality improvement and overall C sequestration.

In the Bio system, the amount of accumulated C in the AG residue ranged from 103.78 g m^{-2} C (s. barley) to 221.96 g m^{-2} C (w. rye) and almost the same amount – 218.8 g m^{-2} C was also accumulated in the buckwheat AG harvest residue (Table 7). The amount of C accumulated in the integrated system was at least twice as much, ranging from: 251.02 g m^{-2} C (s. barley) to 414.29 g m^{-2} C (w. rye) using Int-low-N input system and; from 281.53 g m^{-2} C (s. barley) and 288.49 g m^{-2} C (s. wheat) to 451.11 g m^{-2} C (w. triticale) using Int-high-N input system.

Table 7. Accumulated C (g m^{-2}) in DM of above-ground residue using different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	195.18 ± 23.08^a	343.62 ± 11.52^b	381.73 ± 11.68^c
S. wheat	139.85 ± 11.11^a	265.51 ± 7.70^b	288.49 ± 7.97^c
W. rye	221.96 ± 22.66^a	414.29 ± 55.11^b	434.87 ± 52.40^c
W. triticale	142.23 ± 17.05^a	393.36 ± 29.34^b	451.11 ± 40.78^c
S. barley	103.78 ± 6.58^a	251.02 ± 11.12^b	281.53 ± 10.63^c
S. oat	138.54 ± 8.69^a	264.02 ± 14.95^b	309.19 ± 13.69^c
Buckwheat	215.80 ± 9.92^a	259.39 ± 14.36^b	334.61 ± 16.84^c

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

Both for the purpose of improving soil fertility and greatest possible C assimilation, it is desirable to increase the proportion of crops in the crop rotation that form a voluminous root system and large above-ground biomass also. This could help for the sequestration of a significant amount of C and will contribute to the increase in soil organic matter, especially in cases where the contribution of organic matter will be formed not only from the root mass, but also the surface crop residues will be left on the field. It would be especially important to follow this using organic system management, where crop productivity is usually lower and crops are forced to compete with weeds 'in a natural way' and there are limited opportunities to achieve a rapid increase in yield by using mineral fertilizers.

The amount of C accumulated in BG residue was significantly lower (11–27% depending on crop species, 21% on average) than that accumulated in AG residue (Table 8). In Bio system it ranged from 23.64 ± 0.95 g m^{-2} C (buckwheat) and 24.96 ± 1.42 g m^{-2} C (s. barley) to 46.62 ± 6.89 g m^{-2} C (w. rye). Relatively high uptake by the root system was also ensured by other winter cereals - w. triticale (37.89 ± 6.16 g m^{-2} C) and w. wheat (28.01 ± 1.78 g m^{-2} C). Among spring cereals, the greatest C uptake was provided by s. oat (36.05 ± 2.76 g m^{-2} C), as during growing season they develop a large root system even in more modest soil conditions. This crop is also perfectly suitable for cultivation using organic cropping system. Below ground carbon input to soil by root biomass is among the most important variables driving soil C dynamics in agroecosystems. As C allocation below ground is the primordial pathway for C to enter soil, promotion of crop growing with large root system may play a decisive role in soil C sequestration (Pierret et al., 2016; Kell et al., 2017). Roots often contribute more to SOC due to a higher degree of carbon stabilization than that of aboveground biomass (Poeplau et al., 2015; Bjornsson & Prade, 2021).

Table 8. Accumulated C in below-ground residue (g m^{-2}) in different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	39.26 ± 5.26^{a}	55.72 ± 4.46^{b}	54.58 ± 4.15^{c}
S. wheat	28.01 ± 1.78^{a}	48.22 ± 1.71^{b}	48.05 ± 1.69^{c}
W. rye	46.62 ± 6.89	59.46 ± 10.46	61.70 ± 10.55
W. triticale	37.89 ± 6.16^{a}	64.83 ± 8.36^{b}	70.0 ± 9.53^{c}
S. barley	24.96 ± 1.42^{a}	35.83 ± 0.98^{b}	37.27 ± 0.81^{c}
S. oat	36.05 ± 2.76^{a}	47.70 ± 1.40^{b}	46.35 ± 1.37^{c}
Buckwheat	23.64 ± 0.95^{a}	26.82 ± 1.05^{b}	31.37 ± 1.14^{c}

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

Using the integrated system, the greatest C uptake by root biomass among winter crops was caused by w. triticale (64.83 ± 8.36 g m^{-2} C and 70.0 ± 9.53 g m^{-2} C in Int-low-N and Int-high-N system, respectively) rather than w. rye (59.46 ± 10.46 g m^{-2} C, and 61.70 ± 10.55 g m^{-2} C); among spring crops it was s. wheat (48.22 ± 1.71 g m^{-2} C and 48.05 ± 1.69 g m^{-2} C in Int-low-N and Int-high-N system, respectively) rather than s. oat (47.70 ± 1.40 g m^{-2} C and 46.35 ± 1.37 g m^{-2} C). The mentioned crops are intensively grown crops that are very responsive to N fertilizers. Data analysis show that more stable species in all cropping systems was w. rye, for which C uptake by BG residue did not differ significantly among cropping systems. Hirte et al. (2018) concluded that fertilization has only little potential to alter absolute amounts of BGC inputs to deep soil in order to sequester C in the long term.

In previously conducted studies found that root biomass C of winter wheat ranges between 40 and 125 g m^{-2}; median of 9 studies – 60 g m^{-2} (Hoad et al., 2001; Williams et al., 2013; Hu et al., 2018). Root biomass in low-intensity systems was found to be similar as or even higher than that in high-intensity systems (Chirinda et al., 2012; Lazicki et al., 2016; Hirte et al., 2018). This is in line with the results of our research, where we found that below-ground residue and accumulated C of w. wheat in the integrated system with low N input be equivalent and even slightly higher than in the system with high N input (Tables 6, 8).

Proportionally, the largest amount of accumulated C in the BG residue compared to that accumulated in the AG residue in Bio system was for w. triticale and s. oat - 27 and 25%, respectively; the lowest – only 11% was for buckwheat. In the integrated system, the amount of C accumulated by BG residue was proportionally lower - on average 15% in Int-low-N (fluctuated between 10–18% depending on the species) and 14% in Int-high-N (fluctuated between 10 - 18% depending on the species).

In integrated system, the total amount of accumulated C in AG and BG residue varied within the following limits: 128.74 ± 7.01 g m^{-2} C (s. barley) - 268.57 ± 28.68 g m^{-2} C (w. rye) using Bio cropping system; 286.21 ± 15.24 g m^{-2} C (buckwheat) and 286.85 ± 11.59 g m^{-2} C (s. barley) – 473.75 ± 64.85 g m^{-2} C using Int-low-N system; 318.79 ± 11.09 g m^{-2} C (s. barley) – 521.11 ± 46.26 g m^{-2} C (w. triticale) using Int-high-N system (Fig. 5). Hirte et al. (2018) found that the shift in whole-plant C allocation for wheat towards AG biomass with increasing fertilization intensity entailed 10% higher C allocation below ground in organic than conventional farming.

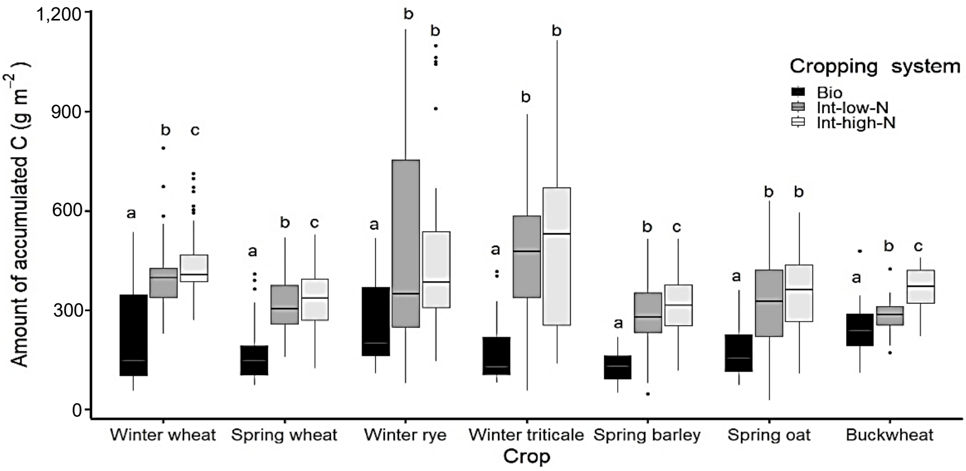

Figure 5. Total amount of accumulated C (g m^{-2}) by cereal in AG and BG residue in different cropping systems.

The amount of N accumulated by AG residue ranged within the following limits: 3.18 ± 0.47 g m^{-2} N (w. triticale) – 6.45 ± 0.3 g m^{-2} N (buckwheat) in Bio system; 8.29 ± 0.50 g m^{-2} N (s. oat) – 11.33 ± 0.98 g m^{-2} N (w. triticale) in Int-low-N system; 11.1 ± 0.45 g m^{-2} N (s. barley) – 15.67 ± 1.69 g m^{-2} N (w. triticale) in Int-high-N system (Fig. 6).

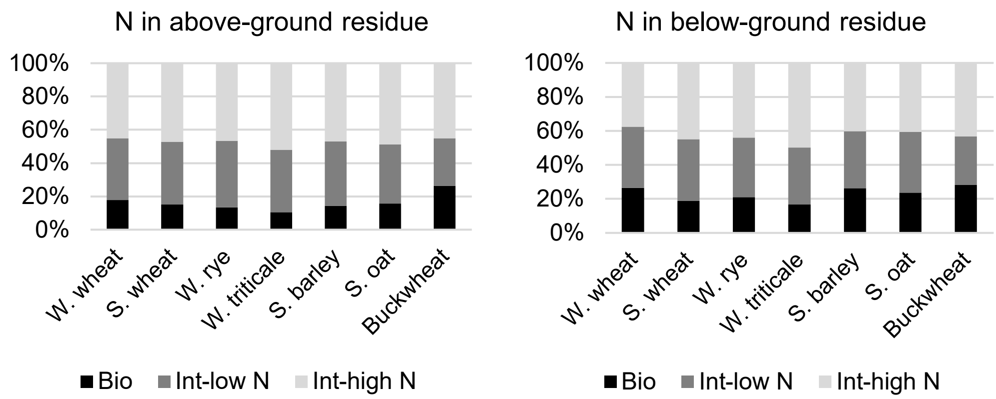

Figure 6. The proportion of nitrogen (N) accumulated by above-ground and below-ground residue in different management systems.

The amount of N accumulated by below-ground residue ranged within the following limits: 0.43 ± 0.04 g m^{-2} N (buckwheat) – 0.82 ± 0.13 g m^{-2} N (w. rye) in Bio system; 0.44 ± 0.03 g m^{-2} N (buckwheat) – 1.36 ± 0.27 g m^{-2} N (w. rye) in Int-low-N system; 0.66 ± 0.04 g m^{-2} N (buckwheat) – 1.71 ± 0.36 g m^{-2} N (w. rye) in Int-high-N system. Comparing the systems, proportionally the highest amount of N with both above-ground and below-ground residue was accumulated in the Int-high-N system; the lowest in the Bio system (Fig. 6).

CONCLUSIONS

The amount of cereal crop residue and accumulated carbon (C) and nitrogen (N) varied significantly depending on the crop species and cropping system. The highest amount of total harvest residue and accumulated C in all cropping systems was produced by winter cereals - rye was on the top: 268.57 ± 28.68 g m^{-2} C using Bio cropping system; 496.57 ± 62.54 g m^{-2} C using Int-high-N system. In the Bio system, high biomass of buckwheat allowed them stably to compete with rye - the total amount of accumulated C by crop residues was 239.4 ± 10.50 g m^{-2} C.

Although a higher total harvest residue was produced using integrated system with high N input, higher proportion of root biomass cereals formed using organic cropping system.

The amount of accumulated N, depending on the crop and cropping system, varied quite significantly: the highest amount by BG and AG residue in the Bio system bound buckwheat – 6.88 g m^{-2} N; in the integrated system w. triticale – 12.6 g m^{-2} N (Int-low-N) and 17.56 g m^{-2} N (Int-high-N).

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Performance and emissions of an agricultural diesel engine with hydrogen injection under different load modes

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Abstract. Excessive use of fossil fuels in transport sector in the last decades stimulated rise in global energy consumption in such way leaving harmful effects on human health and environment. The scale of decarbonization of transport sector in the next decade could be challenging for European Union (EU) as demand for renewable energy, like wind, solar and hydro, will definitely rise. The aim of this study is to find whether hydrogen could be optimal solution for emission reduction in agricultural machinery. In this regard, research was carried out with KOHLER KDI 1903 M diesel engine looking on main performance parameters, as also regulated emissions operating engine with conventional diesel fuel and different hydrogen injection volumes under different loads. Fuel consumption was measured with AVL KMA Mobile device, while emissions was determined using AVL SESAM FTIR exhaust gas analytical system. During the tests, it was observed that the addition of a higher hydrogen concentration provides more substantial benefits that includes a larger impact on fuel consumption and carbon dioxide (CO_2) emissions. Other emissions such as carbon monoxide (CO) emissions had smaller but positive impact, while the addition of hydrogen gas had various impact on nitrogen oxide (NO_x) emissions. At the same time decrease in particulate matter (PM) emissions was observed with higher hydrogen concentrations and more substantial impact was observed during higher load conditions and higher hydrogen concentration.

Key words: diesel engine, emissions, hydrogen addition, performance, torque.

INTRODUCTION

Increased demand for vehicles and excessive use of fossil fuels in transport sector in the last decades stimulated rise in global energy consumption in such way leaving harmful effects on human health and environment. In that case a number of policies designed and implemented to reduce GHG emissions from road transport. Most important is an ambitious global action plan, called Paris Climate Agreement, accepted in 2015 by 196 countries aimed to limit the global warming to 1.5 °C (UN-FCCC, 2015) and most of these nations also signed of the Glasgow Climate Pact at COP26 in 2021 with an unprecedented reference to the role of fossil fuels in the climate crisis. In this regard, road transport plays a significant role in creation of emissions counting around 760 million tonnes of emitted O_2 in the EU in 2022 increased by 24% since 1990 (Destatis, 2024).

The scale of decarbonization of transport sector in the next decade could be challenging for European Union (EU) as demand for renewable energy, like wind, solar and hydro, will definitely rise. This issue is particularly relevant for battery electric vehicles (BEV), the number of which grows significantly based on EU plans to limit the production of vehicles with internal combustion engines already in 2035. This continuous growth of BEV could help mitigate the emissions from on-road applications and practically such vehicles charged with renewable electricity are the only technology able to reduce air pollutants to zero (Philibert, 2018). At the same time there are still many transportation modes, which cannot be easily electrified (e.g., trucks, marine, aviation) (Delgado et al., 2023) as requires high amount of energy, which is not possible to store and transport using existing batteries without significant increase of the weight of them. Thus, the demand for liquid fuels will definitely remain from 2035 and onwards until another suitable solution will be found. However, the choice of the right fuel is not as simple task as it seems as reduction of all most important emissions is not so obvious even using different alternatives (Kryshtopa et al., 2021).

The usage of hydrogen in internal combustion engines (ICEs) is a promising solution looking on a whole life cycle perspective (Baldinelli et al., 2024), which could not only help to improve ecological indicators, but also ensure development of hydrogen usage technologies for ICEs (Kryshtopa et al., 2024). Hydrogen could be considered as the cleanest fuel with a minimal impact on the environment (Abanades, 2012; Obergruber et al., 2018) showing many different properties allowing to achieve more complete combustion and reduction of emissions: higher calorific value and burning velocity, wider flammability range, low diffusivity, etc. As hydrogen does not involve carbon atom as it is in case of liquid fuels, therefore reduction of CO and CO_2 emissions is more visible (Karagoz et al., 2015). Although hydrogen can be injected directly or indirectly showing advantages for each of those methods, the most popular option for using hydrogen in existing diesel ICEs without significant investments, is hydrogen assisted dual-fuel technology allowing to use compressed natural gas (CNG) equipment that has been known for years (Smigins, 2017; Smigins et al., 2020). At the same time, it should be remembered that the proportion of hydrogen should be as high as possible to achieve the desired effect when using two fuels.

The importance of the hydrogen additive amount is also confirmed by Liew (Liew et al., 2010), who conducted study with 6-cylinder, turbocharged Cummins ISM370 diesel engine. He confirmed that the effect of the addition of hydrogen gas (H_2) on combustion process is more visible based on the load and the added amount of hydrogen, showing that relatively large amount of H_2 at higher loads could substantially increase peak pressure and reduce combustion duration.

Shirk also came to similar conclusions (Shirk et al., 2008) testing 1.3 L, 66 kW compression ignition engine on a chassis dynamometer with hydrogen flow rates equivalent to 0%, 5%, and 10% of the total fuel energy. He observed that relatively small amounts of H_2 can be used in light-duty diesel engines, but the benefits on combustion performance and emissions are also relatively small.

Santoso (Santoso et al., 2013) also did not find significant benefits in H_2 introduction at the flow rate of 21.4, 36.2, and 49.6 L min^{-1} testing direct injection diesel engine in dual fuel mode under constant load (10 Nm) and engine speed (2,000 min^{-1}). At the same time, he observed efficiency decrease at low load with hydrogen enrichment.

Less pollution and better performance was observed also by Saravanan (Saravanan & Nagarajan, 2008), who tested single cylinder stationary diesel engine. Tests showed reduction of NO_x emissions more than 5 times using 90% hydrogen enrichment with 70% engine load.

Akbalik (Akbalik & Arpa, 2024) investigated water vapor and hydrogen injection into a single-cylinder diesel engine Antor 4LD 820 LY3 on engine performance and exhaust emissions. He found out increase in engine power and decrease in specific fuel consumption, as also NO_x emissions at higher engine speeds using hydrogen injection.

In general, many studies have been carried out on hydrogen addition in diesel engines, especially in diesel dual-fuel technology engines. When analysing previous research, it can be established that the addition of hydrogen gas to diesel engines can have a positive impact on greenhouse gas emissions depending on the concentration of hydrogen gas versus diesel fuel and engine load. Typically, when running an engine in a dual fuel mode, hydrogen is used to replace the base fuel, so as a result less fossil fuel is consumed. With that, the carbon-based emissions tend to decrease. The properties of hydrogen as well as the concentration of gas affects the combustion process and emissions.

The goal of this research was to analyse the impact of various small concentrations of hydrogen on exhaust gas emissions and fuel consumption by using identical concentrations in different engine speed and load conditions, thus observing a broader spectre from low to high load and different concentrations of hydrogen gas in relation to intake air and fuel.

MATERIALS AND METHODS

Kohler KDI 1903M agricultural engine was used for the research at the Alternative Fuels Research Laboratory of the Latvia University of Life Sciences and Technologies. Engine parameters can be observed in Table 1.

Table 1. Kohler KDI 1903M parameters

Parameter	Value	Unit
Power	31 (42) @2600 min^{-1}	kW (hp)
Torque	133 @1,500 min^{-1}	Nm
Displacement	1,861	cm^3
No. of cylinders	3	-
Bore	88	mm
Stroke	102	mm
Fuel injection	Mechanical rotary pump, direct injection	-
Cooling	Liquid cooling	-
Intake system	Naturally aspirated, 2 intake valves per cyl.	-

As a fuel for engine used commercially available diesel fuel complied with standard EN 590 with a renewable component of 7% added to diesel fuel. The engine was operated with conventional diesel fuel and different, constant hydrogen injection volumes (5, 10, 15 and 20 L min^{-1}) at constant testing modes (1,500 min^{-1} and 2,500 min^{-1} at 5 kW, 10 kW and 15 kW). The flow of hydrogen gas was controlled using digital mass flow meter calibrated for hydrogen use with a measurable flow range from 0 to 50 litres per minute.

For the hydrogen flow control a rotameter with an identical flow range was used. The resulting device (see Fig. 1) allows for a stable and repeatable hydrogen flow adjustment and measurement. The hydrogen gas was supplied with a constant pressure of 0.1 MPa. After the digital mass flow meter, the gas was supplied to the engine intake manifold and further dispersed in the cylinders via the vacuum created by the intake strokes. Hydrogen used in the tests was provided by Linde Gas Latvia. The parameters of hydrogen gas used can be observed in Table 2.

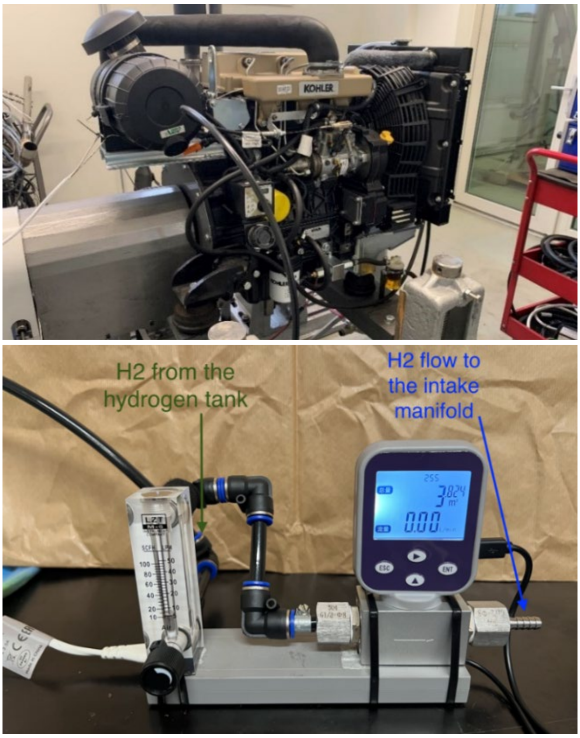

Figure 1. Engine with a test bench and hydrogen flow meter.

Table 2. Hydrogen gas properties

Parameter	Value	Unit
Density	0.0838	kg·m^{-3}
Autoignition temperature	858	K
Minimum ignition energy	0.02	mJ
Flame velocity	265–325	cm s^{-1}
Flammability limits (volume in air)	4–75	%
Purity	99.99	%
Heating value	119.9–141.9	MJ kg^{-1}
Hydrogen tank pressure	20	MPa
Manifold injection pressure	0.1	MPa

Tests with previously mentioned engine were realized on the SIERRA CP-Engineering engine test bench with an AC dynamometer. CADET control system used to control test bench, where the ABB 4 drive system was applied to load equipment more precise. Engine torque was obtained from the test bench using the load cell method. Emissions were recorded by the AVL SESAM FTIR system, where they were analysed by an infra-red spectrometer. In overall, AVL SESAM FTIR allows to fix 24–27 gases simultaneously, from which most part of components is measured, but some components are calculated from the process. The parameters for the test bench can be observed in Table 3. During the tests all gases were fixed, and more detailed analysis were done for regulated (NO_x, CO, CO_2, PM) emissions. AVL KMA Mobile fuel consumption measuring device with measuring range from 0.35–150 L h^{-1} and measurement error - 0.1% was used for fuel consumption measurements.

Each reading was repeated five times and after that the results were averaged to reduce uncertainty. The accuracy of measurements is shown in the graphs using statistical analysis with the assumption that 95% of results should be within 2 standard deviations of the result (± 2σ). Microsoft Excel software with the statistical analysis ToolPak add-in was used for calculating the mean (average) value and standard deviation. For use in graphs, the standard deviation was doubled. The mean value calculated using the statistical analysis provides a 95% confidence level that corresponds with the 2 standard deviations.

Table 3. Test bench parameters

Parameter	Value	Unit
Sierra CP Engineering 51.5 kW AC Dynamometer		
Absorbing power	50	kW
Absorbing torque	140	Nm
Inertia	0.068	kgm^2
Engine speed	7,500	min^{-1}
Electric current	140	A
Current type	3-phase	-
Drive type	Four quadrant regenerative drive	-
Measurement uncertainty	5	%
AVL SESAM FTIR spectrometer for exhaust gas analysis		
Sample gas flow	10	L min^{-1}
Response time	1	s
Measured gas components	CO, CO_2, H_2O, NO, NO_2, N_2O, NH_3, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_6, C_2H_5OH, CH_3OH, CH_3CHO, CHO, HCOOH, SO_2, IC_5, NC_5, NC_8, HNCO, HCN, COS, AHC, NO_x, NMHC, HCD, HCG, HCE	-
Measurement uncertainty	0.11–1.4	%

The maximum flow value of 20 L min^{-1} was chosen because it was the highest concentration of hydrogen that the engine could utilise without modifications to injection timing and engine parameters. Further increasing hydrogen concentration resulted in audibly observable engine knocking or increased engine speed at the lowest operating conditions (idle speed with no added load) that have not been analysed in this research. The selected maximum flow rate has been further divided into multiple segments, resulting in the flow rates (5, 10, 15 and 20 L min^{-1}) that have been tested. As a result, both hydrogen rich (H2 concentration in relation to diesel fuel is high) and hydrogen lean (H2 concentration in relation to diesel fuel is low) mixtures would be obtained in both high load and low load conditions.

RESULTS AND DISCUSSION

During the experiment the engine output power and engine speed were kept as constant variables. The addition of hydrogen gas resulted in the necessity to lower the amount of fuel delivered. As a result, the added hydrogen replaces diesel fuel in the fuel-air mixture resulting in a decrease in fuel consumption. The combustion properties of hydrogen mixed with the change in the fuel-air mixture result in a shift in emission gas concentration.

As it is visible in the graph displayed in Fig. 2, the engine torque remains largely unchanged during the tests with added hydrogen gas. Since the engine speed and load were fixed parameters, and the changes have been implemented to the fuel injection system, and parts of the diesel fuel have been replaced with hydrogen gas, such result could be expected. Since other engine mechanical output parameters such as engine speed and load were unchanged, it is reasonable to expect that parameters like torque will also remain unchanged. This gives valuable information that adding a hydrogen injection system to existing internal combustion engines will not result in a decrease in engines mechanical output parameters.

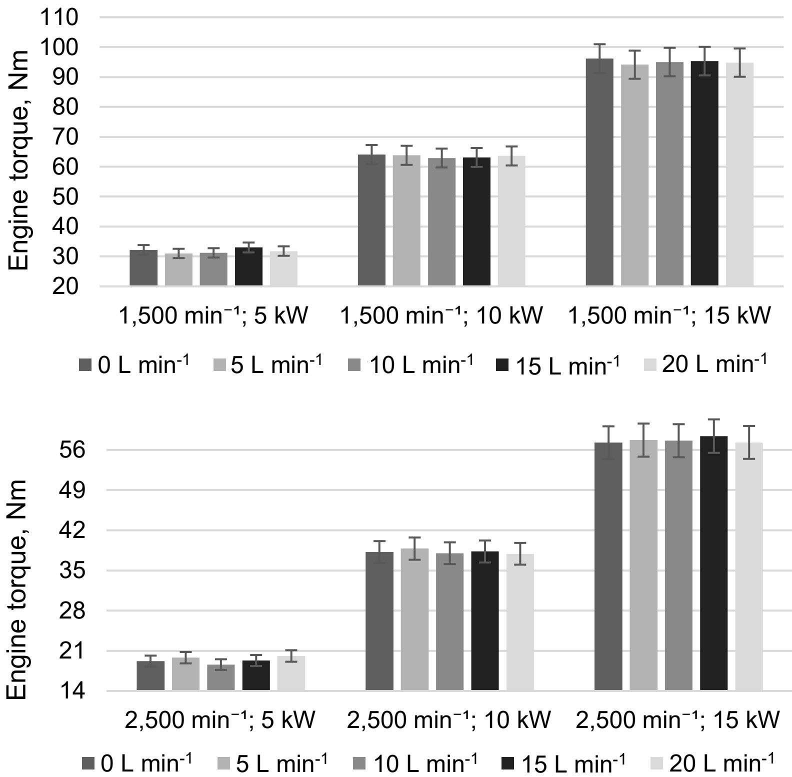

Figure 2. Variation of engine torque under different load modes and hydrogen flow rates.

As it is seen in Fig. 3, the addition of hydrogen gas resulted in a decrease in fuel consumption in all observed engine speed and load conditions. The largest decrease in fuel consumption at all engine speed and load conditions was observed with the addition of 20 L min^{-1} of hydrogen. The largest decrease (up to 41%) in fuel consumption was observed at 1,500 min^{-1} with the added load of 5 kW. With the same addition of 20 L min^{-1} of hydrogen at 2,500 min^{-1}, the reduction of fuel consumption reached nearly 21%.

The smallest reduction in fuel consumption was obtained at 2,500 min^{-1} with 15 kW load and with the addition of 10 L min^{-1} of hydrogen gas (only 3%) as the amount of the hydrogen gas supplied is a fixed value, independent of the amount of diesel fuel injected at the same time. At higher engine speeds and load conditions when the overall fuel and intake air consumption is increased, the overall amount of diesel fuel, air and oxygen that is replaced with the additional hydrogen gas is smaller, resulting in both a lower percentual decrease in fuel consumption and emissions. For comparison, at 1,500 min^{-1} in all load conditions, the same flow rate of hydrogen gas was used, 5, 10, 15 and 20 L min^{-1}, but the fuel consumption as well as the flow of air and oxygen necessary for the combustion process have increased resulting in a decrease in hydrogen gas concentration.

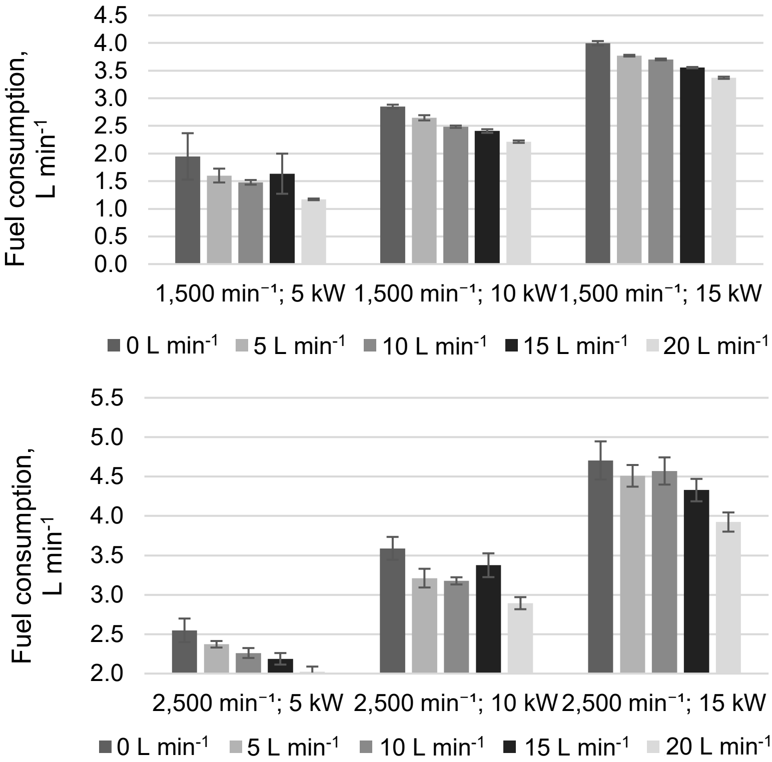

Figure 3. Variation of fuel consumption under different load modes and hydrogen flow rates.

As it is seen in Fig. 4, CO_2 emissions reduced in all engine speed and load conditions. The maximum reduction of CO_2 emissions (up to 28%) was observed at 1,500 min^{-1}, with 5 kW of load and 20 L min^{-1} of hydrogen. With increased engine speed of 2,500 min^{-1} and at the same 5 kW load condition, the reduction in CO_2 emissions was significantly smaller (15.3%). This can be explained by the fact, that the hydrogen gas concentration is decreased. The biggest impact on CO_2 emissions observed with higher concentrations of H_2 gas.

The addition of only 5 L min^{-1} of hydrogen gas resulted in the smallest decrease in CO_2 emissions. At 2,500 min^{-1} with 15 kW of load, the 5 L min^{-1} addition of hydrogen resulted with a 0.7% decrease in CO_2 emissions. The reduction of CO_2 emissions in the exhaust gasses can be explained with the fact that diesel fuel is being removed from the engine and replaced with hydrogen gas. Since hydrogen gas does not contain carbon elements, the overall reduction in carbon-based emissions was observed. When the hydrogen gas concentration in the air-fuel mixture increased, the effect became more visible.

Comparing both the changes in CO_2 emissions and fuel consumption, it was observed that the graphs have a similar tendency - the bigger the impact of hydrogen gas on fuel consumption, the more it affects CO_2 emissions. Again, the carbon particles are being removed from the air-fuel mixture, and the lesser the hydrogen concentration, the less effect on CO_2 emissions the gas has.

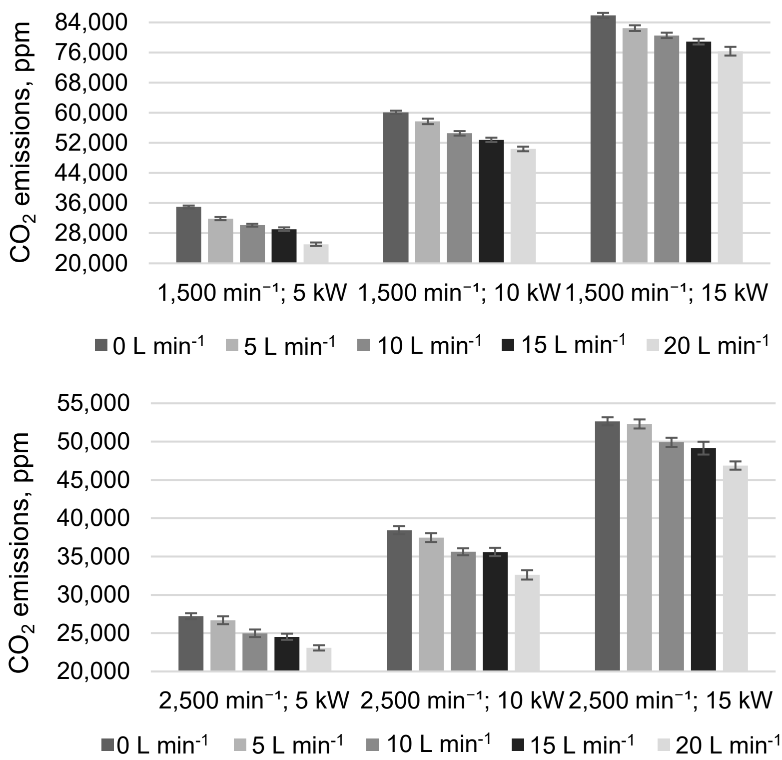

Figure 4. Variation of CO_2 under different load modes and hydrogen flow rates.

As it is seen in Fig. 5, CO emissions also was reduced in all engine speed and load conditions. The largest decrease was observed at 1,500 min^{-1} with 15 kW of added load showing decrease up to 55%. At 2,500 min^{-1} with 15 kW of load the addition of 5 L min^{-1} of hydrogen gas showed a slight increase in CO emissions (up to 3.2%).

Carbon monoxide is a by-product of incomplete combustion. In diesel fueled engines, CO forms during combustion inside the cylinder in zones where the air-fuel mixture is lean, and the insufficient mixing of oxygen and diesel fuel is realized. Since four stroke diesel engines are direct injection, and the fuel injection is realized close to the top dead centre, the formation of both fuel rich and fuel lean areas could be observed. In the case of fuel rich areas, the lack of oxygen prevents the complete oxidation of carbon inside the fuel, but in the case of fuel-lean areas the lower combustion rate and temperature negatively impacts the oxidation of carbon (Tutak et al., 2023).

Since hydrogen has faster flame speed than diesel fuel, it can increase the temperature inside the cylinder, especially during the end of combustion, resulting in a more complete combustion and oxidation of carbon particles. Additionally, since the amount of diesel fuel is reduced, the formation of fuel-rich areas also can be reduced, further aiding reduction of CO emissions (Zareei et al., 2024).

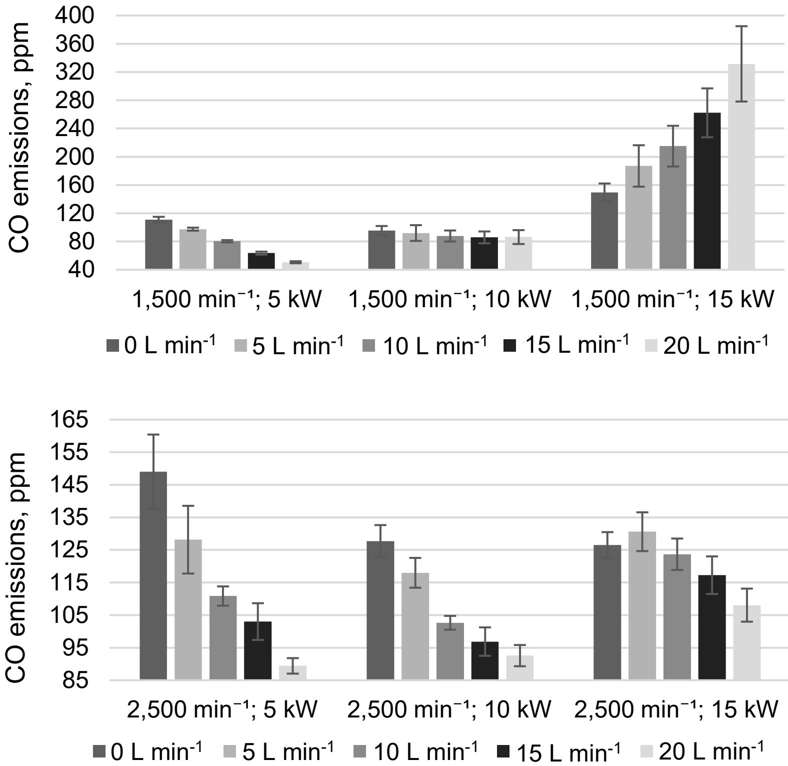

Figure 5. Variation of CO emissions under different load modes and hydrogen flow rates.

Fig. 6 shows changes of PM emissions, where a decrease in PM was observed with higher hydrogen concentrations and more substantial impact during higher load conditions.

Similar to other emissions observed during the tests, the most significant impact on PM emissions was observed with larger concentrations of H_2 gas. At 1,500 min^{-1} with 20 L min^{-1} of hydrogen and 15 kW of added load a 37.2% reduction in particle matter was observed. Overall, with 20 L min^{-1} of hydrogen in both engine speed modes tested a reduction of over 25% was observed, however, with smaller concentrations of hydrogen (at 1,500 min^{-1} with 5 kW of load and 10 L min^{-1} of hydrogen), a maximum increase in PM emissions of up to 3% was obtained.

Particulate matter results from an incomplete combustion of hydrocarbon fuels and forms inside the engine during combustion process. Soot particles make up approximately 50% of particulate matter. Diesel engines produce particulate matter mainly because of the local fuel-rich areas that have incomplete combustion. Since the addition of hydrogen gas reduces both the injected fuel quantity and creates a more homogenous air-fuel mixture, lower particulate matter emissions can be achieved (Hosseini et al., 2023).

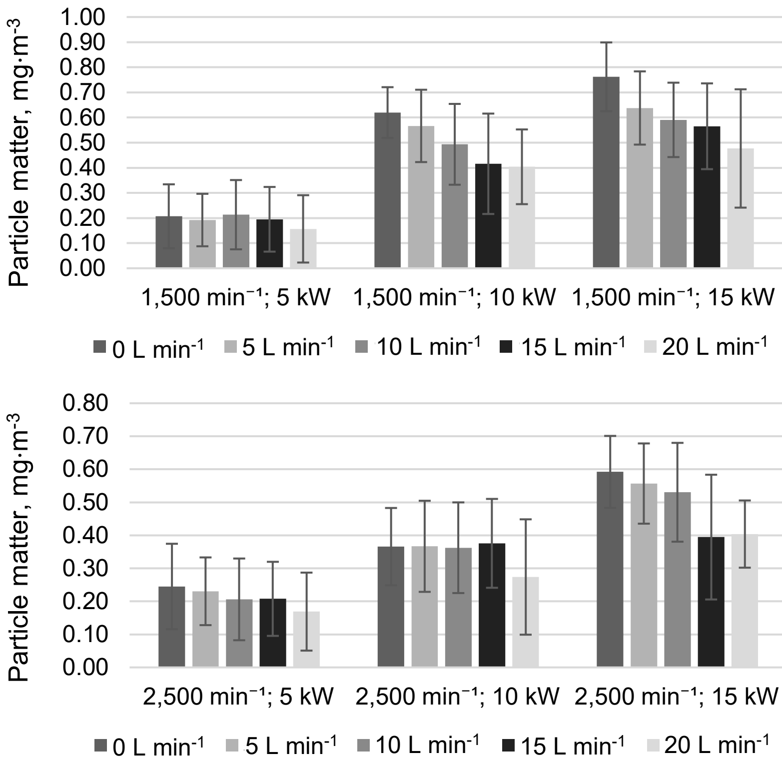

Figure 6. Variation of PM emissions under different load modes and hydrogen flow rates.

The addition of hydrogen gas has various impact on NO_x emissions (see Fig. 7). At the engine speed of 2,500 min^{-1} with 5 kW of added load the addition of hydrogen gas resulted in a reduction in NO_x emissions (up to 13.2%). This reduction can be explained by the fact that hydrogen replaces the diesel fuel in the combustion process, resulting in a leaner combustion process. Additionally, at high engine speed with low load conditions the temperature of combustion is reduced (White et al., 2006). As it is known, NO_x formation happens at high combustion temperatures. As a result, with operational conditions that contain higher engine speed and low load conditions (as the situation with 2,500 min^{-1} with 5 kW load), a decrease in NO_x emissions was achieved.

Additionally, since the hydrogen is added to the engine trough the intake manifold, the added hydrogen gas results in a lower concentration of oxygen that further limits the formation of NO_x (Tsujimura & Suzuki, 2017). Saravanan (Saravanan & Nagarajan, 2008) also found that at full load NO_x emission increases despite to decrease of particulate matter by 50%.

Alternatively, at higher engine load conditions, such as the ones displayed at the engine speed of 1,500 min^{-1} in all load conditions, as well as at 2,500 min^{-1} with 10 and 15 kW of added load, was observed that the NO_x emissions tend to increase. This happens as at higher load conditions the addition of hydrogen gas to the combustion process results in an increase in both the peak in-cylinder pressure and peak heat release (Dimitriou & Tsujimura, 2017). As a result, the chemical processes related to NO_x production are stimulated and more NO_x emissions are produced at these conditions.

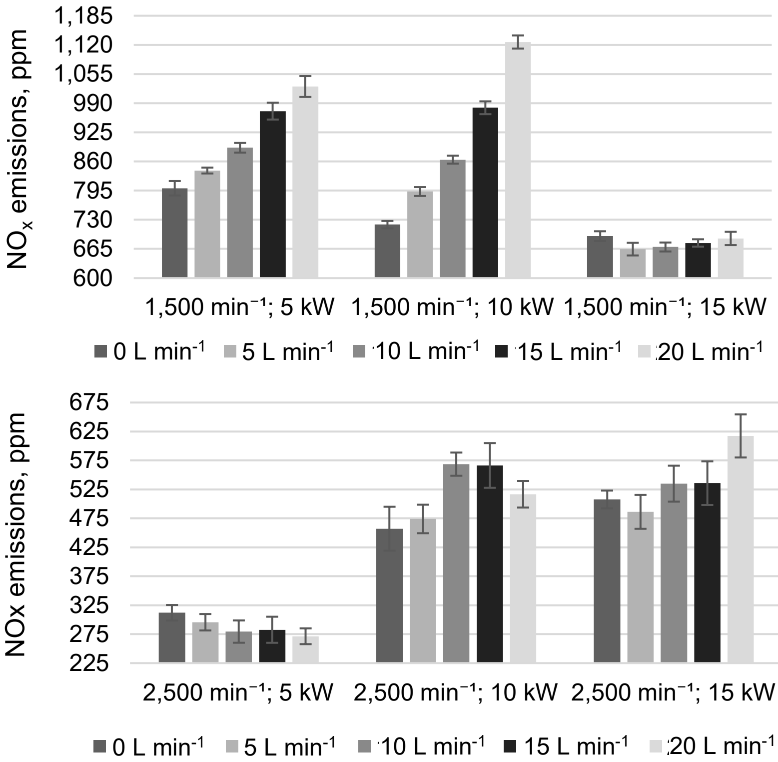

Figure 7. Variation of NO_x emissions under different load modes and hydrogen flow rates.

The most significant increase in NO_x emissions was observed at 1,500 min^{-1} with 10 kW of added load and 20 L min^{-1} of added hydrogen. At this experimental mode, the 36.2% increase in NO_x emissions was obtained.

CONCLUSIONS

Overall, the addition of hydrogen gas to a diesel internal combustion engine can provide multiple benefits, including a reduced fuel consumption, a more complete combustion, and lower greenhouse gas emissions, but the main conclusions are as following:

1. The addition of hydrogen gas to the combustion process and replacing diesel fuel with hydrogen gas has no significant impact on engine output parameters such as torque and the ability to handle load.
2. Higher concentrations of hydrogen gas have more significant impact on emissions and fuel consumption.
3. Hydrogen gas can be used to partially replace diesel fuel, resulting in a decrease in diesel fuel consumption of up to 41%.
4. Addition of hydrogen gas results in a decrease in CO_2 emissions by up to 28.3% at 1,500 min^{-1}, with 5 kW of load and 20 L min^{-1} of hydrogen.

5. Hydrogen gas can impact the combustion process, resulting in up to 55% decrease in CO emissions. At higher load conditions, a slight increase of 3.2% was observed.

6. At higher concentrations of 20 L min^{-1} of hydrogen, up to 37.2% reduction of particle emissions was observed, but with lower concentrations at lower load conditions, an up to 3% increase was observed.

7. At low load conditions and high engine speed when the engine moves high amounts of air and the combustion temperature is lower, an up to 13.2% reduction in NO_x emissions was observed.

8. At higher load conditions, an up to 36.2% increase in NO_x emissions was observed.

The most important negative drawback of hydrogen injection in an internal combustion diesel engine is the increase of NO_x emissions that could be observed during high engine load conditions where the temperature and pressure during combustion is increased. In situations like this, a method for slowing down the combustion process by removing excess heat would be beneficial.

Further research on the impact of hydrogen gas on combustion properties, emissions and fuel consumption is planned.

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Analysis of the potential of livestock excreta for urea production through anaerobic digestion: challenges and opportunities in Latin America

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Abstract. Urea is one of the most demanded fertilizers worldwide and in Latin America. The high dependence on international markets to meet the region's urea demand, the high consumption of fossil energy for its production, and greenhouse gas emissions increase agricultural production costs and create the need to seek alternative processes for urea production to reduce these adverse effects. In this sense, this work explores the possibility of producing urea in Latin America from the ammonia and CO_2 generated in the anaerobic digestion process of livestock excreta under conditions that favor the production of both gases. The results indicate that it is possible to meet the demand for urea for agricultural use by utilizing 15% of its theoretical potential obtained from livestock excreta. This new alternative for obtaining urea brings economic benefits, reduces greenhouse gas emissions, and fosters social development. However, it faces legal, infrastructure, and technological barriers that may hinder the adoption of this technology in rural areas of Latin America.

Key words: anaerobic digestion, fertilizer, Latin America, livestock excreta, urea.

INTRODUCTION

Currently, the world's population stands at 8.2 billion people and is expected to grow by up to 17% by 2054 (United Nations Department of Economic and Social Affairs (Population Division), 2024). Particularly, the growth rate is higher in developing countries, increasing the demand for agricultural products, meat, and consequently a greater consumption of fertilizers and a large generation of agricultural and livestock waste (Mukhtar, 2023). This scenario raises the need for increased exploitation of minerals and high fossil energy consumption to produce fertilizers rich in nitrogen (N), phosphorus (P), and potassium (K), which are the macronutrients involved in cultivating plant species (Zhao et al., 2016).

Urea is the most used fertilizer as a source of N, accounting for about 65% of global application (Zhang et al., 2023), due to its high N content – around 46% – and the fact that its solid form facilitates transportation and reduces volatilization compared to liquid fertilizers (Wang et al., 2021). According to information reported by the Food and Agriculture Organization (FAO), between 2018 and 2022, Latin America (LA) increased its imports of urea, exceeding 11.5 million tons per year, as well as its consumption for agricultural use, which was over 3.4 million tons per year (FAO, 2025). Additionally, it is projected that by 2050, global demand will increase by between 50% and 75% (Lim et al., 2021). The high level of imports and low local production of urea in LA cause fluctuations in its local price due to its dependence on the international market, which at the end of 2021 and the beginning of 2022 - at the onset of the conflict between Russia and Ukraine - reached a historic maximum, exceeding USD 1,200 per metric ton (Bolaños-Silva, 2023). The volatility in the price of fertilizers like urea directly impacts the production costs of agricultural and livestock foods in LA, which could be mitigated by local production that meets part of its demand.

On the other hand, the increase in the use of urea as a fertilizer and the consumption of fossil fuels for its production are responsible for 5% of CO_2 emissions (Gao & Cabrera Serrenho, 2023). This environmental issue is accompanied by a greater generation of animal excreta, due to the growth of the livestock sector, requiring adequate management to avoid methane emissions into the atmosphere and the pollution of soil and water bodies (Samoraj et al., 2022). In this context, the mitigation of environmental problems caused by urea production through the conventional Haber-Bosch process has been addressed by technologies that reduce the use of fossil fuels, enable the capture of CO_2 as a raw material, and seek to increase process efficiency (Erfani et al., 2024).

In the research carried out by Palys & Daoutidis (2024), modifications to the conventional Haber-Bosch process are analyzed by producing hydrogen via water electrolysis and extracting nitrogen from the air using solar photovoltaic and wind energy for its subsequent transformation into ammonia. Additionally, the use of biogenic CO_2 as a reagent to produce urea is proposed, employing ammonia obtained from renewable energies. The researchers conclude that these modifications reduce greenhouse gas emissions by not using natural gas to obtain hydrogen and by incorporating renewable energies to meet part of the energy demand required in the process. Furthermore, the use of biogenic CO_2, derived from bioethanol production, contributes to reducing the use of fossil carbon that is utilized in the conventional process. Similar conclusions were reached in the study by Wang et al. (2021). These researchers expand mitigation strategies, showing that the inclusion of bioenergy as another source of renewable energy and the recovery of heat during urea production significantly reduce emissions of polluting gases if these actions are also aligned with an efficient use of urea through correct planning and the implementation of appropriate practices in agricultural processes, as proposed by Zhang et al. (2023).

Instead, pollution mitigation associated with livestock waste has mainly been tackled through conventional technologies such as composting for recovering nutrients in the solid phase, and anaerobic digestion (AD) technology for the controlled production of biomethane and nutrient recovery in the liquid and solid fractions of the digestate (Dalke et al., 2021). Specifically, the use of AD has taken on greater relevance due to the importance of biomethane as renewable energy. Many studies have focused on optimizing the process to increase production, with one of the main challenges being to avoid ammonia (NH_3) inhibition of methanogenic microorganisms, which are responsible for methane production in AD (Jiang et al., 2019; Yang et al., 2024). However, the production of NH_3 and CO_2 during the AD of livestock excreta can be beneficial, as both substances are a biogenic source for urea production and, additionally, the energy consumption of AD for NH_3 production is lower than that required in the Haber-Bosch process.

Based on the above, a gap in the current state of knowledge is identified. Although several studies have explored the operational conditions of anaerobic digestion (AD) that favor the production of ammonia (NH_3) and carbon dioxide (CO_2), there is still no quantitative assessment of the theoretical potential for urea production from livestock excreta in Latin America, nor an analysis of how such production could help meet the fertilizer demand in the region.

In this sense, the scientific purpose of this study is to estimate the potential for urea production from livestock excreta in Latin America using anaerobic digestion technology under conditions that favor the generation of NH_3 and CO_2. Additionally, the practical purpose is to evaluate whether this process could represent a viable alternative to conventional urea production, considering that this new approach may reduce agricultural input costs, decrease greenhouse gas emissions, and promote the development of a rural industry based on the bioeconomy, while also acknowledging the existing challenges related to infrastructure, legal frameworks, and social aspects in Latin America.

MATERIALS AND METHODS

Urea trade, livestock and manure production data

The information on urea trade and the livestock sector in LA was obtained for the last 5 years reported in the FAO, (2025). Specifically, the analysis includes 34 Latin American countries for which consistent and comparable data were available, including: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay, and other Caribbean countries. Latin America, as defined in this study, covers an estimated area of approximately 20.1 million square kilometers, representing about 13% of the world's land surface (Latin America & Caribbean Surface Area 1961–2025 | MacroTrends, 2025). The region encompasses a wide variety of climate zones, including tropical, subtropical, arid, temperate, and highland climates. This climatic diversity influences both livestock production systems and fertilizer demand across the region (FAO, 2012). The selected components of the urea market were the imports, exports, production, and use in agriculture for each country in the region between 2018 and 2022. Similarly, for the livestock sector, data were extracted regarding the inventory of bovine, swine, and poultry animals between 2019 and 2023. From this information, the total annual amount was calculated by year and by type of livestock for each of the components of the urea trade and for the animal inventory in LA. The totalized results allowed for an analysis of the behavior and projection over time of the urea trade and the animal inventory.

Based on the studies and characterizations of livestock excreta reported by American Society of Agricultural Engineers (ASAE) (2005), for each livestock species, the average excreta production rate per animal (kg animal^{-1} day^{-1}) and the average nitrogen concentration in the excreta per amount excreta (g kg^{-1}) were obtained. This information was subsequently used to estimate the amount of nitrogen available annually for each type of excreta.

Anaerobic digestion conditions for ammonia production

The AD conditions that favor NH_3 production are determined under the assumption that they are close to generating inhibitory effects caused by nitrogenous species (NH_3 and NH_4^+) present in the process. To identify these operating conditions, an analysis was conducted of current research focused on determining the characteristics and parameters that influence AD inhibition and toxicity by nitrogenous species. For this purpose, the following search equation was constructed and used in the Elsevier (2025): (‘anaerobic digestion’ OR ‘biogas production’) AND (‘ammonia production’ OR ‘NH3 production’) AND (‘cattle manure’ OR ‘bovine manure’ OR ‘pig manure’ OR ‘poultry manure’ OR ‘chicken manure’) AND (‘optimization’ OR ‘operating conditions’ OR ‘efficiency’) AND (‘pH’ OR ‘temperature’ OR ‘organic loading rate’ OR ‘hydraulic retention time’).

The results produced by the search equation were filtered between 2018 and 2024 for research articles and review articles. From the filtered documents, an analysis was performed of articles focused on the efficiency of pilot-scale or industrial-scale AD of bovine, swine, and poultry excreta under pH, temperature, organic loading rate (OLR), and hydraulic retention time (HRT) conditions that favor NH_3 and NH_4^+ production.

Urea potential modeling

The previously obtained and analyzed information is used to estimate the potential for urea production and the percentage of its demand that can be met in LA. This estimation was carried out through six calculation steps described below.

Step 1: Calculation of the average annual population for each livestock species. Based on data provided by FAO (2025), the average annual population (number of animals) per species is estimated using the initial and final livestock inventory for each year:

$$AP_{i,j} = \frac{S_{i-1,j} + S_{i,j}}{2} \tag{1}$$

where i indicates the year from 2018 to 2023, j indicates the livestock species (bovine, swine, or poultry), $AP_{i,j}$ in (animal year^{-1}), is the average population, and $S_{i,j}$ in (animal year^{-1}) is the animal inventory for year i of species j, while $S_{i-1,j}$ in (animal year^{-1}) is the animal inventory from the previous year for species j.

Step 2: Calculation of the annual production of livestock excreta. The annual production of excreta for each type of livestock species is calculated from its average annual population and the average daily mass factor of excreta produced per animal using the following expression:

$$AMP_{i,j} = AP_{i,j} \times MD_j \times 365 \tag{2}$$

where $AMP_{i,j}$ in (kg year^{-1}) is the excreta production in year i of species j and MD_j in (kg animal^{-1} day^{-1}) is the daily excreta production factor per animal for species j.

Step 3: Calculation of organic nitrogen. The amount of organic nitrogen is estimated from the average concentration of inorganic and total nitrogen contained in each type of excreta reported by American Society of Agricultural Engineers (ASAE) (2005), as follows:

$$ON_{i,j} = AMP_{i,j}\left(CN_{T,j} - CN_{I,j}\right) \quad (3)$$

where $ON_{i,j}$ in (g year^{-1}) is the annual amount of nitrogen contained in the excreta of species j, while $CN_{T,j}$ in (g kg^{-1}) and $CN_{I,j}$ in (g kg^{-1}) are the total and inorganic nitrogen concentrations in the excreta of species j, respectively.

Step 4: Calculation of ammonia production. A percentage of the total amount of ammonia that can be produced from AD comes from the biological conversion of organic nitrogen, while the remaining percentage is obtained through the complete transformation of inorganic nitrogen into this substance. To calculate the total amount of ammonia, the contribution from organic nitrogen and from inorganic nitrogen is estimated using the following expressions:

$$NH_3^{AD}{}_{i,j} = ON_{i,j} \times R_{AD,j} \quad (4)$$

$$NH_{3}^{I}{}_{i,j} = AMP_{i,j} \times CN_{I,j} \quad (5)$$

$$NH_3^T{}_i = \sum_j NH_3^{AD}{}_{i,j} + NH_3^I{}_{i,j} \quad (6)$$

where $NH_3^{AD}{}_{i,j}$ in (g year^{-1}) y $NH_3^I{}_{i,j}$ in (g year^{-1}) is the production in year i from the excreta of spicie j coming from organic and inorganic nitrogen, respectively. $R_{AD,j}$ in (g g^{-1}) is the yield of organic nitrogen conversion to ammonia through AD of the excreta of species j and $NH_3^T{}_i$ in (g year^{-1}) is the total amount of ammonia produced in year i.

Step 5: Urea production from ammonia. The production of urea ($CO(NH_2)_2$) from gaseous ammonia and carbon dioxide is limited by the stoichiometry and yield of the following reaction (Erfani et al., 2024):

$$2NH_3 + CO_2 = CO(NH_2)_2 + H_2O \quad (7)$$

Therefore, the expression that allows the estimation of urea production is the following:

$$UP_i = NH_3^T{}_i \times 1.765 \times R_U \quad (8)$$

where UP_i in (g year^{-1}) is the annual amount of urea produced, and R_U in (mol mol^{-1}) is the reaction yield for its production.

Step 6: Percentage of satisfaction of the urea demand. The analysis of data on the urea market in LA made it possible to calculate the total amount of urea used annually for agricultural purposes in the region. Therefore, the expression used to estimate the percentage of urea demand that can be covered by the urea produced from the AD of livestock excreta is the following:

$$PDS_U = \frac{UD_i}{UP_i} \times 100 \quad (9)$$

where PDS_U is the percentage of satisfied urea demand, while UD_i in (g year^{-1}) is the annual amount of urea used in agriculture for LA.

RESULTS AND DISCUSSION

Urea in Latin America

The urea market in LA was studied based on four factors reported in the FAO (2025): exports, imports, production, and agricultural use. Fig. 1 shows the behavior of the first 3 factors in the last 5 reported years, while Fig. 2 shows the amount of urea used in agriculture. Based on the information in Fig. 1, annual urea production has decreased each year, from 3.8 million tons in 2018 to 2.8 million tons in 2022, while imports increased in 2020 and 2021 to over 14 million tons, but then decreased again in 2022 to the levels exhibited in 2018 and 2019, not exceeding 12 million tons. The observed increase in urea imports during 2020 and 2021 may have been caused by the increase in local food production during the COVID-19 health crisis. This analysis is corroborated by the increase in the tons of urea used for agriculture reported for 2021 (Fig. 2).

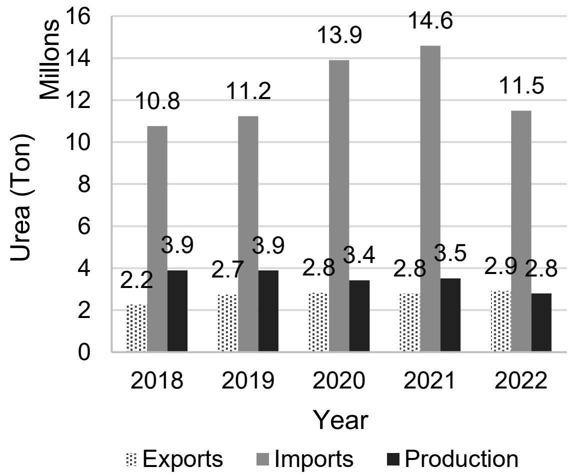

Figure 1. Urea Latin America trade.

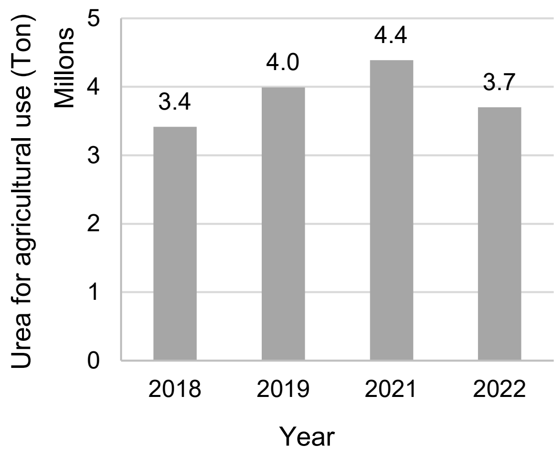

Figure 2. Urea for agricultural use in LA.

Regarding the levels of urea exported by LA, they have remained constant at around 2.8 million tons, indicating that LA has a stable market for urea sales. Moreover, it can be observed that urea import levels are higher than the levels of urea used in agriculture, representing at most 35% of the imported tons. This indicates the existence of other markets for urea in LA that can be supplied by local production, thus reducing costs in those markets.

Livestock in Latin America

Livestock production for bovine, swine, and poultry species is shown in Figs. 3–5, respectively. Each species exhibits sustained growth in animal population, with the poultry sector having the largest population – 3,936 million animals in 2023 – while the smallest population is in the swine sector, with 103 million animals in that same year.

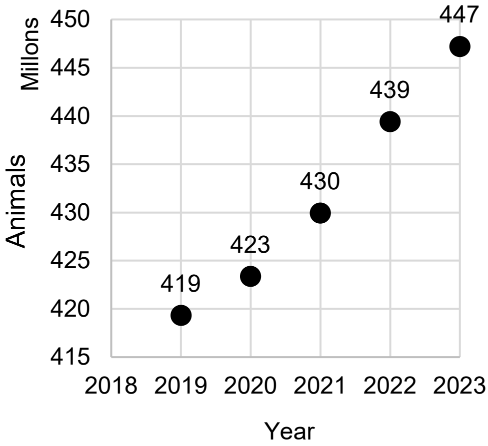

Figure 3. Cattle average population.

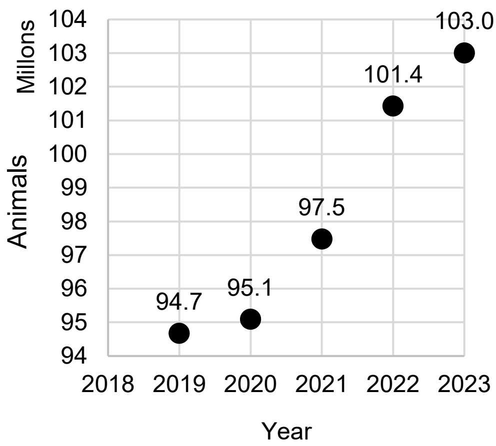

Figure 4. Pig average population.

The bovine sector shows a total increase of 6.6% between 2019 and 2023 and an average annual increase of 1.6%. Similarly, the total and average annual increase percentages for the swine sector are 8.8% and 2.1%, and for poultry 8.3% and 2.0%, respectively. These results and the highly linear trend exhibited by annual growth in animal populations for each species allow for low-uncertainty projections regarding future average populations, and thus in estimates concerning the volume of excreta and its nitrogen content.

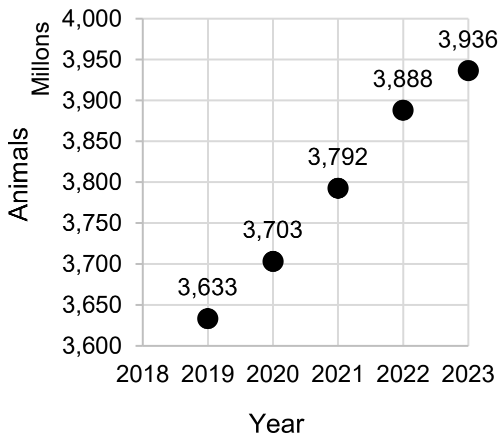

Figure 5. Chicken average population.

Furthermore, it is important to note that the swine and poultry sectors have intensive production systems, and therefore, collecting their excreta is technically less complex. These two sectors show the highest growth rates, whereas the bovine sector displays the lowest growth rate; in addition, there is greater difficulty in collecting bovine excreta due to the extensive nature of bovine production in much of LA.

Available nitrogen from livestock manure in LA

Table 1 shows the values of excreta production and the inorganic and total nitrogen content for each species reported in American Society of Agricultural Engineers (ASAE) (2005). Using these values and Equations 2 and 3, the amount of total and organic nitrogen contained in the excreta of each species is estimated.

Fig. 6 compares the total nitrogen content in the excreta of each species, showing that bovine excreta contain the highest amount of nitrogen due to the large amount of excreta produced per animal. Additionally, Table 3 presents the regression coefficients (R^2), which indicate the linear trend followed by the data series shown in Fig. 6. The slope values show that the total nitrogen content increases on average by 340,613, 23,504, and 46,185 tons per year for cattle, pig, and chicken manure, respectively. However, the poultry sector has the highest nitrogen concentration, and the swine sector the lowest. These characteristics of the excreta indicate that co-digestion of swine excreta with one of the other two types can shift the carbon/nitrogen ratio (C/N) toward nitrogen and, therefore, make it possible to increase NH_3 production through AD.

Table 1. Manure characteristics

Species	Production (kg animal^{-1} day^{-1})	Total Nitrogen (g kg^{-1})[2]	Inorganic Nitrogen (g kg^{-1})[2]
Cattle[1]	22.0	5.9	1.8
Pig[1]	3.8	5.3	3.0
Chicken[1]	0.088	18.2	10.0

[1]Data extracted from American Society of Agricultural Engineers (ASAE) (2005);

[2]Nitrogen concentration per kg of manure.

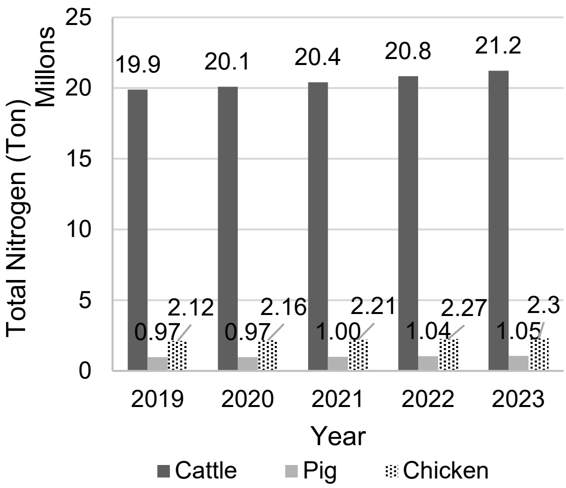

Figure 6. Urea for agricultural use in LA.

Anaerobic digestion conditions to produce ammonia

Ammonia production from anaerobic digestion requires a C/N below 20 and an alkaline pH in the reactor so that methanogenic bacteria are inhibited - preventing methane production – and allowing the transformation of ammonium ions into ammonia. However, a high pH also inhibits acidogenic bacteria, which are responsible for the deamination of amino acids and favor the formation of ammonium ions (Astals et al., 2018; Jiang et al., 2019; Yang et al., 2024). In this sense, the strategy proposed to increase the production and accumulation of ammonium ions, preventing the inhibition of acidogenic bacteria and allowing their subsequent conversion into gaseous NH_3, is to carry out AD in two stages.

The first stage is carried out under conditions that favor hydrolysis and acidogenesis, aiming to maximize the breakdown of complex organic compounds into amino acids and volatile fatty acids, thereby releasing and accumulating organic nitrogen in the form of ammonium ions (NH_4^+). Meanwhile, the second stage is carried out under conditions that shift the chemical equilibrium of the ammonium ion toward gaseous NH_3 and inhibit methanogenic microorganisms. Table 2 shows the operating conditions for each of the proposed stages. Additionally, in both proposed AD stages, there is continuous CO_2 production due to the decomposition of carbon-containing molecules; hence, the products with the highest concentration in the gas phase are NH_3 and CO_2.

Table 2. Anaerobic digestion conditions

Step	Process	C/N	pH	Temperature (°C)	Hydraulic retention time (day)	Product of interest
1	Hydrolysis and Acidogenesis	10–20	5.5–6.5	35–37	2–5	NH_4^+
2	Advanced Deamination		8.0–9.0	50–60	10–20	NH_3
Global conversion of AD[1]		Cattle manure: 60% – 75%; pig manure: 70% – 85%; chicken manure: 80% – 90%				

[1]The ranges are approximate for each type of manure and are obtained from the analysis of various research (Astals et al., 2018; Jiang et al., 2019; Samoraj et al., 2022; Yang et al., 2024).

Urea production and satisfaction of demand in Latin America

Fig. 7 shows the estimated ammonia production from the anaerobic digestion of excreta for each species. Ammonia production exhibits a linear growth trend for the whole species. Table 3 presents the regression coefficients (R^2), which confirm the linear trend followed by the data series shown in Fig. 7. The slope values show that the ammonia production increases on average by 244,717, 19,324, and 42,028 tons per year for cattle, pig, and chicken manure, respectively. From this behavior, the total ammonia production expected for 2025 is approximately 18.9 million tons, and considering a 95% yield for the urea production reaction (Eq. 7) (Palys & Daoutidis, 2024), about 31.5 million tons of this fertilizer could be obtained for the same year.

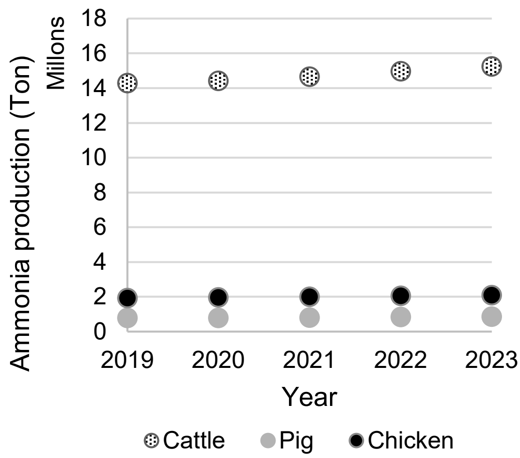

Figure 7. Ammonia production estimated in LA.

Finally, with this result, it can be observed that by utilizing 15% of the estimated potential for urea production, it would be possible to meet the demand for urea for agricultural use in LA, which still does not exceed 4.5 million tons per year (see Fig. 2). Regarding the annual urea imports, which have ranged between 10.8 and 14.6 million tons, they could be met if 47% of the estimated potential from the AD of livestock excreta were utilized.

Table 3. Lineal regression parameters

Figure	Variables	Species	Slope (ton year^{-1})	Y-intercept (ton)	R^2
Fig. 6	Total Nitrogen (predicted variable) year (independent variable)	Cattle	340,613	2×10^7	0.98
		Pig	23,504	9×10^5	0.94
		Chicken	46,185	2×10^6	0.99
Fig. 7	Ammonia production (predicted variable) year (independent variable)	Cattle	244,717	-5×10^8	0.98
		Pig	19,324	-4×10^7	0.94
		Chicken	42,028	-8×10^7	0.99

Advantages and barriers to urea production in LA

The implementation of AD technology focused on ammonia production for its subsequent conversion into urea in LA offers significant advantages, but at the same time, faces different barriers that must be overcome.

Among the advantages are economic benefits, reduced environmental impacts, and social development. Economic benefits are achieved because local urea production from livestock excreta can reduce dependence on international production and prices, stabilizing local prices and lowering production costs in the agricultural sector. Moreover, this would improve food security and strengthen the region's economy. With respect to reducing environmental impacts, producing NH_3 and CO_2 via AD significantly decreases greenhouse gas emissions compared to the conventional Haber-Bosch process, which requires temperatures above 400 °C and pressures exceeding 150 bar, while AD can operate at a maximum temperature of 50 °C and at atmospheric pressure. Additionally, the proper management and utilization of excreta would greatly reduce soil and water pollution. Further advantages related to social development stem from job creation in rural areas by adopting new technologies such as the one proposed here, technological investment in the agricultural sector, and improvements in education focused on teaching more appropriate management and utilization of livestock waste.

On the other hand, the barriers to be overcome are associated with the technological and infrastructural limitations present in LA for medium- and large-scale AD implementation, as well as the high initial investment required. Moreover, in many LA countries there are no regulatory frameworks or clear policies to encourage the use of new technologies for urea production. Finally, another major barrier is the unfavorable perception that farmers may have regarding these technologies; thus, government programs and demonstration projects showcasing the benefits of their implementation would be key strategies for achieving acceptance in the rural sector.

CONCLUSIONS

Anaerobic digestion focused on NH_3 production also produces CO_2, making it possible to obtain the reactants for urea production in a single process with low pressure and low energy consumption. The demand for urea for agricultural use can be met by utilizing 15% of the estimated potential, which reduces dependence on imports and problems associated with fertilizer price volatility in the international market. All the environmental benefits arising from adopting this technology – such as proper excreta management, reduced greenhouse gas emissions, and waste utilization – help guide the agricultural sector toward a circular economy. The feasibility of implementing this technology requires closing gaps with governmental support through the creation of specific policies aimed at improving infrastructure, providing financing, developing training programs, and enhancing the quality of life of the rural population.

Future research should focus on estimating the actual technical potential for urea production from anaerobic digestion, considering the technological and infrastructural limitations in Latin America, as well as on long-term evaluations of process sustainability.

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Review: unmanned aerial vehicles and artificial intelligence in precision agriculture

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Abstract. To meet the needs of sustainable intensification in crop and animal production, farmers use a set of technologies which are referred to as Agriculture 4.0 to 5.0 or digital agriculture. Differences compared to traditional precision farming techniques are in extensive use of UAV, smart sensors implemented in machines, crops, animals and in the soil, cloud computing, IoT, together with extensive use of AI for data analyses. Unmanned Aerial Vehicles (UAV), also called drones, have become an essential tool in digital agriculture. UAVs have witnessed remarkable development in the past decades and so in the recent years, the topic of agricultural UAVs has gained the attention of many farmers. The submitted paper provides a review on recent scientific literature dedicated to the utilization of agricultural UAVs. The utilization areas are reviewed in monitoring (remote sensing), interventional applications of various inputs, and other areas of possible utilization. The novelty of this review highlights the importance of the integration of UAVs with artificial intelligence (AI) and the Internet of Things (IoT). Sophisticated artificial intelligence and machine-learning algorithms are developing to analyse UAV-collected data, enhancing the accuracy and efficiency. Machine learning models in combination with artificial intelligence are capable of yield prediction and crop management, effecting future decision-making processes. Several key opportunities can be identified for future research, including the development of more sophisticated decision-making processes and machine learning methods based on artificial intelligence, the automation of agricultural crop production, improved UAV autonomy, and the potential use of UAV swarms in different field operations.

Key words: artificial intelligence, drone; precision agriculture, unmanned aerial vehicle, unmanned aerial spraying system.

INTRODUCTION

The agricultural sector worldwide is facing many challenges, including climate change, social and economic changes, which threaten the food production and food security (Inoue, 2020). The world population is estimated to reach about 10 billion by 2050, affecting the food consumption globally (United Nations, 2024). Furthermore, the total arable-land area is decreasing worldwide due to climate change, desertification, floods and increasing built-up area. Thus, sustainable resource management is crucial to overcome these challenges. To address these challenges, modern farming approaches were developed based on technological advancements.

At first, the allowance of the global positioning systems (GPS) in 1983 for civilian use led to the beginning of precision agriculture in 1992. It was a major step forward due to the ability of the GPS system to geolocate the information about soil and crops. Precision agriculture started the technological revolution of Agriculture 4.0. Precision agriculture is primarily a data-driven approach and is undergoing remarkable changes due to unmanned aerial vehicles (UAV) and their ability to acquire vast amounts of data quickly and efficiently. The hypothesis behind precision agriculture is that each field is not uniform, and both soil and crops have their site-specific needs. The International Society of Precision Agriculture defines precision agriculture as 'a management strategy that gathers, processes and analyses temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production' (Lowenberg-DeBoer & Erickson, 2019; Balafoutis et al., 2020; Ammoniaci et al., 2021; ISPA, 2024; Guebsi et al., 2024; Singh et al., 2024).

Later, smart farming techniques, as an advancement of precision agriculture dealing with the application of information technologies and efficient decision-making processes based on the collected data, has been adopted (Iqbal, 2024). According to the International Organization for Standardization (ISO), smart farming is a data-driven, principled decision-making approach using information communication technology and data analytics in agriculture (ISO, 2023). However, huge development and innovation processes in agriculture indicate the rise of the new technological revolution - Agriculture 5.0, also referred to as 'Digital Agriculture'. Agriculture 5.0 aims to apply information and communication-based technologies (ICT) introduced in Agriculture 4.0 with the focus on Internet of Things (IoT), Unmanned Aerial Vehicles (UAV), Artificial Intelligence (AI) technology, machine learning and deep learning. Digital agriculture can be defined as a combination of two modern farming approaches, i.e. precision agriculture (precision farming) and smart farming. However, in literature, these terms are often being used interchangeably (Javaid et al., 2022; Ragazou et al., 2022; Iqbal, 2024). With the arrival of new technologies within Agriculture 5.0 further streamlining of decision-making processes is expected, bringing fundamental changes in the management and production processes. Multi-criterial decision-making process, which must include adequate reaction to frequent changes in production (climate factors, pests and disease occurrence, uneven distribution of rainfalls) will be possible to realize without human intervention.

Nowadays, the development and implementation of UAV and AI technology plays a crucial role in the innovation processes. This development over the past 5 years had a great acceleration, which brings the importance to be able to orientate in this field of interest and recent trends. Although the current agricultural sector is on the interface of technological revolutions of Agriculture 4.0 and Agriculture 5.0, different levels of revolutions are in practise worldwide, depending on the geographical locations (Iqbal, 2024).

Review Aim

The aim of this review was to point out the future trends and importance of linking the technology of UAV with AI as one of the basic tools of the latest technological revolution Agriculture 5.0. This literature review focused on the utilization of UAV and AI in agriculture crop and animal production. The aim of this review was to provide an up-to-date report on UAV and AI applications in crop and animal production with a critical review of their use in practical farming, as well as research. The information compiled in this paper should identify the existing research needs and promising future research areas.

UNMANNED AERIAL VEHICLES

Unmanned aerial vehicles (UAV) are commonly known as drones or unmanned aircrafts. According to the European Union Aviation Safety Agency (EASA), a UAV can be defined as any aircraft operating or designed to operate autonomously or to be piloted remotely without a pilot (operator) on board. Commonly, the trajectory of flight (UAV flight mission) is predefined, although it can be controlled by an operator (pilot) through remote teleoperation commands from a ground station, affecting its motion and direction. Other terms are also used in UAV terminology, i.e. unmanned aircraft system (UAS) referring to a drone, its system, and all the other equipment used to control and operate it, and remotely piloted aircraft system (RPAS), which is a subcategory of UAS. (Radoglou-Grammatikis et al., 2020; EASA, 2024).

The variety of present UAVs is enormous - varying in characteristics such as size, flight, endurance, capabilities; construction type; specifications or flexibility. Classification of UAVs can be based on aerodynamics features, level of autonomy, size and weight, power source or maximum payload. From the technical and construction type point of view, classification based on aerodynamics features is commonly applied, dividing UAVs into fixed-wing, rotary-wing and hybrid types (Radoglou-Grammatikis et al., 2020; Mohsan et al., 2023; Toscano et al., 2024). According to the construction type, UAVs can be classified as:

Fixed-wing UAVs – These are characterized by the presence of stationary airfoil-shaped wings that generate lift, enabling the aircraft to take off from the ground. The control of fixed-wing UAV is accomplished through elevators, ailerons and rudder that are attached to the wings. These construction characteristics enable UAVs to turn around roll, pitch and yaw angles. Fixed-wing UAVs are operated in higher altitudes, able to cover lager areas, which makes them suitable for large-scale mapping and surveillance missions. However, the operation of this type of UAV requires a skilled pilot, proper training, and suitable take-off and landing areas. Foldable-wing UAVs enhance the portability while maintaining performance comparable to fixed-wing UAVs (Radoglou-Grammatikis et al., 2020; Toscano et al., 2024; Guebsi et al., 2024).

Rotary-wing UAVs – These are composed of one/several rotor/s that generate the appropriate power necessary for lifting. This type does not need a forward airspeed for lifting (unlike fixed-wing UAVs) and is capable of hovering. Rotary-wing UAVs are divided into single rotor-types or multi-rotor types. A single-rotor UAV type (often referred to as helicopter or helicopter-type UAV) features a single set of blades connected to a central shaft, which rotates at a specific speed. However, the manoeuvrability and operation of single-rotor UAVs requires more proper training and skilled operator. A multi-rotor UAV consists of sets of rotors with blades attached, varying from two to eight and more rotors. Depending on the number of rotors, multi-rotor UAVs can be classified into subcategories, e.g. bicopters, tricopters, quadcopters, hexacopters or octocopters. Rotary-wing UAVs are better and easier to control and are capable to carry a heavier payload compared to the fixed-wing type. They can be implemented in more precise and site-specific operations (Radoglou-Grammatikis et al., 2020; Guebsi et al., 2024; Toscano et al., 2024).

Hybrid UAVs – The term hybrid in this context refers to UAVs that combine the features of both fixed-wing and rotary-wing UAVs. Hybrid UAVs possesses rotors for vertical take-off and landing but also include fixed-wings utilised for covering large areas in mapping operations (Radoglou-Grammatikis et al., 2020; Guebsi et al., 2024).

At present, UAVs are being used in multiple applications including military, industrial, research, commercial and civil applications. Furthermore, they are being applied in transportation operations, safety and surveillance missions, search and rescue, etc. As part of the industrial applications, remote sensing operations and precision agriculture operations are involved (Mohsan et al., 2023).

The rise of digital technologies and advanced sensors in the early 2000s led to a broader utilization of UAVs in agriculture. UAVs are highly capable to conduct various tasks in the agricultural sector across multiple areas including remote sensing operations (variability determination, growth assessment, weed detection etc.), mapping, spraying applications (fertilizers and pesticides), fertilizer spreading, seed sowing, transporting certain goods etc. As (Fig. 1) shows, UAV utilization areas can be classified to three categories to which the greatest attention is given, following the UAV monitoring (remote sensing operations), interventional applications and other areasof utilization (Jeongeun et al., 2019; Aslan et al., 2022; Singh et al., 2024).

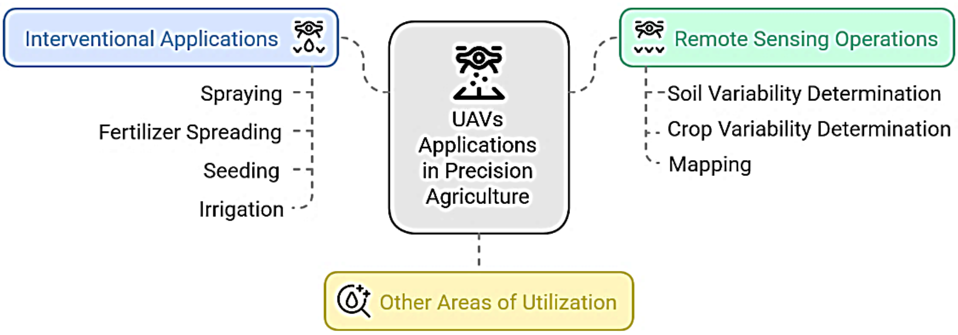

Figure 1. Classification of UAV utilization areas in precision agriculture.

Remote sensing operations

In remote sensing UAV operations, the sensing altitude is crucial. An UAV is included in an aerial monitoring platform, however in terms of sensing, it is on the interface of proximal and remote sensing, as (Fig. 2) shows. Lower operating altitude of the UAV enables to acquire data from shorter distance above the surface of soil/crop similarly to ground-based proximal sensing platforms. It provides images with finer spatial resolution suitable for precise sensing (e.g. plant counting), whereas higher operating altitude is suitable for bigger scale sensing or mapping with lower spatial resolution covering larger areas and increasing the efficiency of sensing.

Sensors utilized in remote sensing operations are passive or active and are exchangeable (dismountable) or built-in parts of different platforms in remote sensing. Passive sensors use natural source of light (primarily Sun) to measure the electromagnetic energy reflected from the Earth surface, whereas active sensors provide their own form of illumination. Examples of the sensors include (Žížala et al., 2021; NASA, 2025) passive sensors (Red Green Blue (RGB), VIS (Visible), multispectral and hyperspectral, thermal) and active sensors (radio detection and ranging (radar), Light Detection and Ranging (LiDAR) and microwave-band based).

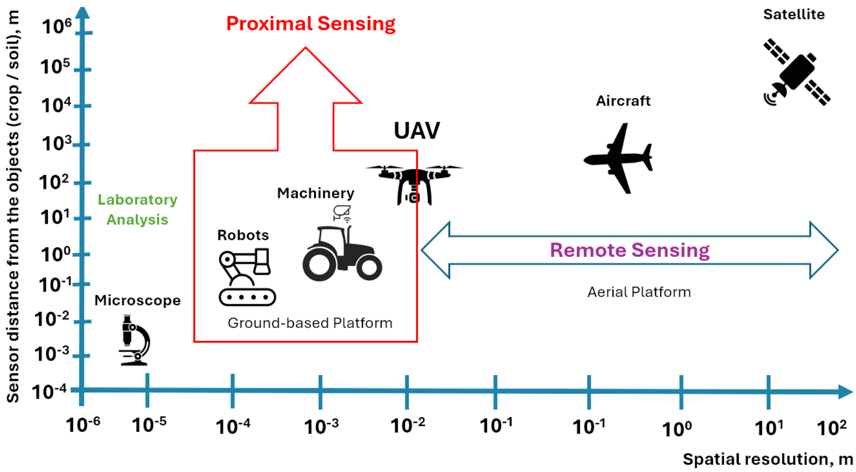

Figure 2. Monitoring platforms in precision agriculture (Modified according to Oerkle, 2019).

The main three remote sensing platforms (also referred to as mobile remote sensing platforms) include satellite-based, airborne-based (aircrafts and helicopters) and UAV-based platforms. Satellite-based platform is a higher-altitude remote sensing method, equipped with various types of sensors and capable of covering larger areas compared to UAV-based platform. However, satellite-based platforms are expensive, and for precision agriculture applications higher-detailed images (with finer resolution) and better data availability are required. These factors are leading to the utilization of UAV-based platform. As mentioned above, this platform is flexible and is capable of both lower-to-ground and higher-to-ground remote sensing with data/images available almost immediately. Image processing techniques are getting more reliable and thus increasingly adopted. The massive development in UAV technology leads to the path of automation, including automated flights and mission planning with minimal human intervention. Moreover, UAVs can be operated at much lower costs in contrast to satellites. Despite the above-mentioned benefits of UAV-based platform, the greatest drawback for their implementation among many farmers is the significantly lower territorial coverage area, flight time (ranging from 30 to 45 minutes) and the requirement for specialized personnel, i.e. trained pilots or operators (Žížala et al., 2021; Phang et al., 2023; Iqbal, 2024).

Understanding the characteristics and the variability of the cultivated soils and crops is crucial for effective crop management. UAVs are a promising technology for soil and crop monitoring due to their versatility of various utilized sensors. For soil monitoring, ground based platforms of proximal sensing are more frequently used nowadays, however, some results were published recently aimed at soil-water regimes and environmental indicators as GHG emissions. Crop monitoring via UAVs typically employs high-resolution imaging techniques aimed at defining vegetation indices and quantitative indicators enabling the monitoring of crop conditions, as well as pests, diseases and weeds. These techniques provide valuable information on parameters such as growth, biomass content, vitality, health status, stress or water content (Toscano et al., 2024). Recently published results in the area of remote sensing operations are summarized in Table 1.

It is evident from Table 1, that almost all indicators of the soil and crop status can be monitored with sensors carried by UAVs. The biggest potential can be seen in areas where a rapid and agile action needs to be done after the soil/crop monitoring as e.g. in the case of pests/disease and weed infection. As for pests and disease, the key role is to identify, characterize and geo-locate the detected irregularities, but also the disease status or level of pest infestation. As Table 1 shows, various sensor can be used for pests and disease identification. Such sensors include (Aslan et al., 2022; Guebsi et al., 2024; Toscano et al., 2024) RGB, VIS, multispectral and hyperspectral sensors. RGB sensors are capable of detection of damaged or infested areas. However, multispectral and hyperspectral sensors are proven to be more efficient and versatile. They are capable of more detailed plant health assessment and early disease detection.

The weed detection process is based on the principle of 'green on brown' or 'green on green'. The 'green on brown' principle identifies the weeds mostly in the pre-sowing process (getting rid of weeds prior to planting), at the early growing stage of primary cultivated crop or after the harvest. The 'green on green' principle identifies the weeds in the early and late growing phase of primary cultivated crop. This principle is more difficult for weed identification. To achieve relevant results, it cooperates with AI, which helps to analyse individual plants and detect features such as colour or shape differences (Kool et al., 2023; Mahmudul Hasan, 2024; Cultiwise, 2025).

Novelty in agricultural application can be seen in UAVs equipped with LiDAR sensors. These are a promising tool for the estimation of biomass and crop structure and crop/tree canopy estimation. Furthermore, LiDAR sensors are included in highly detailed 3D terrain modelling operations. Combining LiDAR data with precise georeferencing techniques allows for the creation of high-resolution soil maps. By analysing variations in surface elevation and slopes, different soil types can be identified, classified and mapped, and their spatial distribution within a field. Such maps provide farmers with valuable data on elevation and spatial distribution of soil surface roughness. Valuable data from mapping also have a potential in validating soil erosion models. Furthermore, high potential of UAVs can be seen in soil surface roughness measurements and estimation using the technology of both LiDAR and Photogrammetry (Alexiou et al., 2022; Farhan et al., 2024; Guebsi et al., 2024).

Table 1. Overview of published results on monitoring (remote sensing) using different sensors carried by UAVs

UAV operation	Property determined	Recent studies	Sensor Type and Analysis Method
Soil variability determination	Soil moisture	Zhang J. et al. (2025)	Multispectral and infrared sensor
	Soil salinity	Zhao et al. (2023)	Multispectral sensor and image texture
	GHG emissions from soil	Fosco et al. (2024)	Special sensor capable to detect and quantify the emissions
	Soil organic matter	Zhou J. et al. (2023)	Multispectral sensor imagery and machine learning algorithm
UAV operation	Property determined	Recent Studies	Sensor Type and Analysis Method
Crop variability determination	Crop emergence	Li et al. (2019)	RGB sensor and semi-automated image analysis software
	Crop classification	Deng et al. (2024)	Multispectral images with object-oriented method and random forest algorithm for crop identification using multispectral UAV images
	Plant counting	Sun H. et al. (2025)	High resolution RGB sensor with lightweight model (P2P-CNF)
	Crop yield estimation	García-Martínez et al. (2020)	Neural network using multispectral and RGB images
		Lukas et al. (2022)	Multispectral imagery and estimation of vegetation indices
	Tree canopy estimation	Cantón-Martínez et al. (2024)	LiDAR sensor and statistical analysis between LiDAR and field measurements
	Water stress detection	Yunhyeok et al. (2021)	Thermal sensor imagery used for further processing
	Nutrient content deficiency	Yu et al. (2023)	Hyperspectral sensor data and machine learning
		Shu et al. (2024)	Multispectral sensor
	Pests and disease identification	Shah et al. (2023)	High-resolution RGB sensor and deep learning algorithm
		Guan et al. (2024)	High-resolution RGB sensor
		Zhang X. et al. (2019)	Hyperspectral imagery and deep learning approach
	Weed identification	Pei et al. (2022)	High-resolution RGB sensor and YOLOv4 weed detection model
Surface mapping	3D terrain modelling of surface, slope, elevation	Alexiou et al. (2022); Farhan et al. (2024); Guebsi et al. (2024)	LiDAR sensor
	Soil surface roughness	Onnen et al. (2020)	Photogrammetry
		Xingming et al. (2021)	LiDAR sensor

Interventional Applications

The utilization of UAVs is no longer limited to remote sensing operations in agriculture, as now they are capable of direct interventions on both crops and soils. Special UAVs are able to conduct precise interventional applications of various inputs. These applications are site-specific applications, including variable rate technology (VRT) and targeted application. Moreover, the application process of various inputs is being automatized, thus the human intervention and human exposure to the inputs are being eliminated (Chen, H. et al., 2021). Table 2 shows the uses of possible inputs for interventional applications and includes recently published studies in this area.

Table 2. Overview of published results on interventional applications of various inputs by UAVs

Input	Interventional Application	Recent Studies	Description
Pesticide	Precision spraying	Arakawa & Kamio (2023)	Application of ultra-low-volume pesticide in chestnut orchards
		Lopes et al. (2023)	Pesticide application in soybeans and evaluation of 4 different nozzle types
		Zhou Q. et al. (2023)	Pesticide application in wheat and performance evaluation of different types of UAVs
Herbicide	Precision spraying	Guo et al. (2024)	Herbicide application in rice fields including a VRT prescription map
		Pranaswi et al. (2024)	Herbicide application in wheat fields and evaluation of different spraying parameters
Insecticide	Precision spraying	Sun T. et al. (2022)	Insecticide application in wheat fields and comparison of droplet distribution under different operation parameters
		Liu et al. (2023)	Insecticide application in alfalfa fields and analysis of the impact of spraying volume on the droplet deposition
		Guan et al. (2024)	Insecticide application in rice fields including a VRT prescription map
Fertilizer (liquid)	Precision spraying	Kharim et al. (2019)	Organic liquid fertilizer application in rice fields and droplet deposition density evaluation
		Xu et al. (2023)	Chelated-zinc fertilizer application to produce zinc-biofortified rice grains
Fertilizer (solid)	Fertilizer spreading	Song et al. (2023)	Fertilizer spreading (granular urea) and analysis of particle deposition distribution of two UAVs under different operational parameters
Seed	Aerial seeding	Zhang S. et al. (2022)	Oilseed rape aerial seeding and parameters optimalization in mountainous areas
Tree seed	Aerial seeding	Castro et al. (2024)	Aerial seeding in the process of forest restoration in inaccessible terrain
Water	Irrigation	Emerging future research area	Site-specific distribution of water in smart irrigation approaches
Pollen	Artificial pollination/ UAV assisted pollination	Alyafei et al. (2022)	Artificial pollination of date palms
		Hulens et al. (2022)	Development of small UAVs capable of autonomous approach of flowers and pollination
Insects	Biological control and beneficial insects release	Martel et al. (2021)	Releasing parasitic insects against an agricultural and forest pest

It is evident from Table 2, that various inputs may be applied by UAVs. As for liquid inputs (pesticides, herbicides, fertilizers etc.), very high potential can be seen in precision spraying. Spraying is the most frequently used UAV interventional application. The popularity of such UAVs is rising mainly in Asia (Japan, China, South Korea, India), Brazil, USA, UK and a few countries of EU. UAVs equipped with spraying systems are also referred to as unmanned aerial spraying systems (UASS). Other terms such as uncrewed aerial vehicle, unmanned aerial system, and remotely piloted aerial application system (RPAAS) are also being used (Ozkan, 2024; UAPASTF, 2024). Furthermore, it is apparent from Table 2 that the recent studies also focused on the parameters of spraying, droplet deposition and evaluation of spraying nozzle types. Further research is needed to study the overall quality and safety of aerial spraying. As for water, UAVs may be used in specific scenarios for water distribution of smaller volumes in smart irrigation processes, and it might be a future emerging research area.

In case of solid inputs (seeds, solid fertilizers), potential can be seen in aerial seeding and fertilizer spreading. Aerial seeding in agriculture and forestry is among the latest possible applications of UAVs. An aerial seeding system consists of an UAV equipped with seed/plant disperse system capable of seeding/ planting, mostly used in inaccessible terrains. High potential of UAVs can be seen in forestry in the process of forest restoration. However, additional research and development is needed in this area to provide more details on the precision of the UAV aerial seeding systems (Jeongeun et al., 2019; Castro et al., 2024). As mentioned earlier, UAV fertilizer spreading technology is another promising area of possible utilization. The spreading system is similar to aerial seeding systems and is suitable for mainly granular fertilizer, both in targeted and VRT applications (Wang, X. et al., 2024; Zhou, H. et al., 2024).

As for non-ordinary inputs (pollen, insects), the novelty of UAV interventional applications can be seen in both artificial pollination and biological insects' release. However, it is important to state that artificial pollination is only an alternative solution to the decline of natural pollinators, not a replacement. Jeongeun et al. (2019) states, that the development of UAV pollinators opens new solutions, such as carrying the pollen in the animal hair coated with gel and placed (taped) on the bottom of the UAV. This area of interest is still developing and needs further research, as well as the biological control and release of beneficial insects.

Other Areas of UAV Utilization

Besides remote sensing operations and interventional applications, precision agriculture opens new areas for possible UAV utilization. High potential of UAV utilization can be seen in animal production, which is a crucial part of the agriculture sector providing both food and animal products.

Livestock production is essential in animal production contributing to food security, nutrition, poverty alleviation, and economic growth. Approximately 30% of the Earth's terrestrial areas are occupied with livestock systems. For high-quality food production and to meet the needs for food safety, animal welfare according to the World Organisation for Animal Health (WOAH) is crucial. Pasture-raised and open-raised environments not only include welfare benefits but also allows UAVs to be utilized in such environments (Soumya et al., 2022; Arulmozhi et al., 2024; WOAH, 2025). UAVs might be used in livestock production for various purposes using UAV imagery and video surveillance. Some of the main areas of utilization according to (Alanezi et al., 2022) are included in Table 3.

As Table 3 shows, there are numbers of possible uses of UAVs in livestock production. For data collection and practical uses, high potential can be seen in operations such as livestock counting, detection, animal position and monitoring of health status and behaviour. Such operations provide valuable data for the implementation with smart technologies and help farmers to easily notice any changes.

Table 3. UAV utilization in livestock production

Area of Utilization	Purpose
Detection and counting	Detecting, locating and counting livestock
Tracking while grazing	Tracking the livestock while grazing Tracking the misplaced livestock
Communication and exploratory agency	Shepherding the livestock Collecting data of livestock position
Health monitoring	Monitoring livestock temperature and blood pressure (UAV in combination with RFID tags attached to the ears of animals)
Behaviour monitoring	Monitoring feeding behaviour Capturing feeding patterns
Livestock roundup	Gathering livestock together
Estimation of livestock distribution	Understanding the spatial and temporal distribution of the livestock in the pastures

The rapid development of UAVs might also influence other operations and processes in animal production. As aquaculture is part of agriculture, UAVs have a potential in the feeding of fish in fishponds. Chavande & Bagde (2024) describe, that in aquaculture, automated UAV systems are revolutionizing the feeding process by distributing feed pellets over ponds at regular intervals. UAVs involved in the feeding process are equipped with a rotary disc placed under the tank, similar to fertilizer spreading and seeding UAVs. The feed (in form of solid granules) is then dispersed from the UAV.

Besides animal production, there are other possible areas for UAV utilization. Table 4 shows more possible areas for UAV implementation and includes recent studies.

Table 4. Other areas for UAV utilization

Area of Utilization	Recent Studies	Description
Environmental studies	Burgués & Marco (2020)	Environmental chemical sensing providing dense 3D air quality measurements
	Almalki et al. (2021)	Real time monitoring of environmental parameters in combination with IoT and ground sensors
Heat loss detection	Tanda et al. (2020)	UAV-based thermal-imaging approach for monitoring of waste disposal sites with focus on detecting heat loss and biogas leakages
Wildlife	Beaver et al. (2020)	Wildlife estimation and monitoring using UAVs with thermal sensors

UAV REGULATIONS AND ADOPTION CHALLENGES

It is evident that the utilization of UAVs in precision agriculture significantly contributes to the agricultural sector. However, it also faces complex challenges and limitations that require particular attention. These challenges can be identified in the following sections.

Regulatory Limitations

Different regulations of UAV operations are applied worldwide. In Europe, the European Union Aviation Safety Agency (EASA) is heading towards the development of harmonized regulations for UAV utilization. Within the member countries of the European Union, the regulatory framework consists of two legal acts - Regulation (EU) 2019/947 (focusing on operational requirements and procedures, e.g. operator registration, remote operator´s certificate) and Regulation (EU) 2019/945 (focusing on technical certification requirements, e.g. design, manufacturing, maintenance and third-country operations). The regulations are also applicable to certain non-EU countries that are part of EFTA (European Free Trade Association), and which participate in the EASA system as part of their ties with the European Union, e.g. including countries Switzerland, Liechtenstein, Norway, and Iceland (EASA, 2024).

In other regions worldwide, civil aviation administrations and authorities are responsible for UAV regulatory. For instance, in China (Civil Aviation Administration of China), in Australia (Civil Aviation Safety Authority) or in the United States of America (Federal Aviation Administrations). However, regulations worldwide may vary, leading to some countries with very strict UAV regulatory frameworks or almost forbidden use of UAVs (Nazarov et al., 2023; Global Drone Regulatory Database, 2025).

The major challenge that persists for broader UAV adoption is the Beyond Visual Line of Sight (BVLOS) operation. Such operations include e.g. large-scale monitoring and sensing of agricultural land. BVLOS operations can be executed under specific conditions and require special permits and operator registrations. Furthermore, when integrating UAV autonomy to BVLOS operations, additional regulatory challenges may appear. BVLOS regulations are currently varying worldwide, thus international harmonization of regulations is highly recommended to enhance the adoption of UAVs in agriculture and unlock their full potential (Matalonga et al., 2022; Nazarov et al., 2023).

One of the strictest regulations regarding UAV utilization is in spraying applications. The potential of Unmanned Aerial Spraying Systems (UASS) is evident; however, it needs further improvement in available data. The strictest regulations apply for UASS pesticide spraying. Many parameters of UASS may affect the overall spraying quality, including the number and position of the rotors; number, type, location and configuration of the spraying nozzles; distance between the nozzles and the vertical distance between the rotors and the nozzles under them. Furthermore, there are several more operational parameters needed to be considered, including flight path planning; spraying height; application rate (volume adjustment); swath width; appropriate nozzle type; droplet penetration rate, deposition and drift (Ozkan, 2024; García-Munguía et al., 2024).

Besides the operational parameters of UASS, the application of pesticides must consider several additional factors, for instance human toxicology; operator and bystander exposure; dietary exposures; environmental fate and behaviour;

ecotoxicology; physical and chemical properties; and efficacy. The most important and vulnerable data for safe UASS applications are related to exposure, efficacy, and spraying drift. Some of the published data on UASS performance may not be relevant and can be contradictory because of the wide variation of design parameters among UASS being tested. Additional research and published data are needed to make conclusive statements on overall safety of UASS applications (OECD, 2021).

Technological Limitations

Although UAV technology has many benefits, it still faces technological limitations that need to be overcome, to maximize its potential. These limitations include lack of technological and communication infrastructure (for isolated and rural areas) leading to troubles with connectivity; UAV battery life and power maintenance; operational parameters - the maximum payload, level of autonomy; sensor reliability and accuracy; overall equipment reliability etc. (García-Munguía et al., 2024; Guebsi et al., 2024; Khan et al., 2024) for instance:

Remote sensing operations – Sensor precision, reliability and acquired data accuracy are crucial, particularly in various climatic conditions, highlighting the need to develop more robust sensors.

Interventional applications – Limited autonomy and restricted maximum payload capacities are currently present, including power, structural and flight safety limitations. The development of light-weight structures with higher payload capacities and improved autonomy is crucial. Additionally, for spraying applications, there is an increasing need for improvements in UAV flexible spray control software, and the incorporation of flow meters to track and record the actual amount of spray applied.

Adoption Barriers

Different adoption barriers regarding UAV utilization may be identified. There are obstacles for slower adoption among farmers, including the high initial costs of UAV technology and software; necessary training and skills development; and lack of knowledge and UAV promotion in this sector. Especially for small farmers it is difficult to allocate resources for the higher initial investment of UAV technology due to the limited access to capital. For rural areas and developing countries, barriers may also include the lack of technological infrastructure; insufficient technical skills of farmers; and the resistance to change. Broader adoption needs better awareness strategies and proper training to enhance the skills of farmers (Kushwaha et al., 2023; Puppala et al., 2023).

Ethical Considerations and Data Privacy

With the easy access to UAV technology and its broader adoption in various sectors, concerns may arise including ethics, privacy and safety. Critical questions may be identified about privacy protection, informed consent, and potential impacts on the interference of built-in and natural environments. In agriculture, these ethical considerations are particularly relevant concerning data collection practices. It is crucial for farmers to follow ethical guidelines and to ensure, that the use of UAV technology respects privacy rights and does not violate the rights of neighbouring landowners or local communities. In terms of data collection, questions about data privacy may arise. It is essential to protect data privacy in today's era of information overload. Secure data storage and transmission is needed to prevent data breaches and data missuses. Moreover, other impacts of UAVs should be considered, including potential environmental impacts, such as disturbances to wildlife or local ecosystems caused by frequent aerial flights (Guebsi et al., 2024; Hoek Spaans et al., 2024).

FUTURE TRENDS AND PROMISING RESEARCH AREAS IN UAV TECHNOLOGY

The UAV technology is rapidly developing in recent years, which leads to a broader utilization of this technology in digital agriculture. As for remote sensing, the future trend is heading towards high-accuracy detailed sensing of both crops and soils, with the emphasis on precise data. Such data would supplement the informational databases of satellite sensed data and significantly contribute to better results, enhancing the decision-making processes. For interventional applications, the future development is heading towards more reliable and safer systems with high level of autonomy and increased maximum payload capacities. Besides these trends, new promising research areas can be identified, following:

Harvesting – The development of harvesting UAVs might be a big frontier in UAV automation. A harvesting UAV equipped with advanced computer vision and robotic arms would be able to identify, precisely pick (harvest), temporarily store and transport the harvested crops. The potential is seen in harvesting fruits and vegetables. Harvesting UAVs would contribute to increased efficiency especially in large orchards or vegetable fields and help to replace the already missing human labour. However, challenges remain in terms of identifying the optimal harvesting time, maximum payload capacity and the ability to handle such crops without causing damage to them (Guebsi et al., 2024; Moshayedi, et al., 2024).

Transporting – The popularity of transporting UAVs is rising in the industrial and delivering sector. However, for agricultural products transportation, challenges remain in terms of maximum payload capacity and the big volumes that are being moved on a daily basis. However, this technology would be suitable for the transport of smaller objects such as spare parts, phytosanitary products and certain goods (Savaniu et al., 2022). Due to the ongoing development of UAVs with bigger and bigger payload capacities, the novelty will be seen in different areas too, such as the transportation of feed, water barrels or animals to remote or inaccessible terrains.

UAVs in Indoor and Controlled Environments – Precision field tasks similar to outdoor UAV operations may be carried out indoors too. This leads to the integration of UAVs in greenhouse environments, as they are well suited for autonomous UAV tasks. For other indoor environments, such as vertical farms, innovation is leading towards the development of micro-UAVs. These micro-UAVs could revolutionize crop management in controlled environments by enabling continuous, non-invasive monitoring and rapid response to changes and problems. However, factors such as the lack of GPS information in an indoor environment, the presence of obstacles and a limited flight area make the UAV control difficult in indoor environments, thus further research and development is needed (Aslan et al., 2022; Guebsi et al., 2024).

As mentioned above, the potential of UAVs can be seen in various new research areas. The recent development leads to the integration of UAVs and Artificial Intelligence (AI). That is already transforming the sector of digital agriculture by optimizing processes and available resources to the new technological revolution Agriculture 5.0. The combination of AI, robotics and UAV techniques is a promising approach towards farm operations optimalization and farm automation processes. Potential of UAV and AI integration can be already seen in crop management, prediction and classification; disease and pest management; soil management; water management and fertigation; weed detection and agricultural supply chain and logistics management (Abreu & van Deventer, 2022; Oliveira & Silva, 2023; Son et al., 2024). As for more complex agricultural systems and technologies, research areas can be identified for the following areas:

UAV Autonomy – The synergy between UAV and AI has led to a notable progress in the autonomy of UAVs, that are capable of completing complex missions without direct human supervision. UAV autonomy can be significantly improved by AI, optimizing processes such as autonomous behaviour and real-time decision-making. Few aspects regarding to UAV autonomy can be identified, as the optimization of UAV trajectories; detection and recognition of objects in real time; and the development of autonomous navigation systems. The synergy of AI and UAV autonomy is a promising research area for future development (Caballero-Martin et al., 2024).

Team Deployment of UAVs (Swarming) – The future direction of UAVs is heading towards the development of AI-driven UAVs and team deployment of UAVs, also referred to as UAV swarming or UAV swarms. The development of UAV swarms could allow more efficient and coordinated monitoring of large agricultural areas and synchronized data acquisition. One of the potential areas of UAV swarm utilization is the development of accurate, real-time, reliable, and autonomous UAV-based systems for crop diseases identification and weed detection. UAV swarms may be utilized in UAV interventional applications, e.g. spraying, fertilizer spreading, seeding. Furthermore, the ongoing development of harvesting UAVs may be a suitable area for UAV swarm utilization in order to increase the harvesting efficiency. However, challenges remain in terms of the optimal UAV path planning, communication, obstacle avoidance and possibilities of malfunctions, thus additional research is needed (Bouguettaya et al., 2022; Ming et al., 2023; Guebsi et al., 2024).

UAV Integration in Unmanned Farms – An unmanned farm is a production model, which does not require human labour for carrying out various operations and tasks. Unmanned farms include a variety of systems for fully automated and intelligent management, such as sensors, Big Data, IoT, 5G, UAV, AI, robots etc. An automated unmanned farm represents the highest level of agricultural production. Various systems are used for monitoring the environment, growth status of agricultural animals and plants, the working status of various operating equipment, efficient data transmission and storage to the clouds. An unmanned farm is capable of precise planning, optimizing every process and self-decision making (Wang, T. et al., 2021; Ming et al., 2023). In particular, UAVs may contribute to the system of an unmanned farm by efficient data collection and precise AI analysis of acquired data. Moreover, the utilization of UAVs in specific field operations (e.g. targeted spraying) and team deployment tasks is a promising tool for the enhancement of unmanned farms. In this context, UAVs significantly contribute to the whole production system of unmanned farms (Ming et al., 2023; Padhiary et al., 2024; Moshayedi et al., 2024).

AI Analysis of Data – Precision agriculture includes enormous amount of farming data related to meteorological information, soil and crop conditions, marketing demands, and land uses. The integration of AI has a big potential in analysing UAV collected data in combination with machine learning and deep learning algorithms (Zhai et al., 2020). Potential can be seen in analysing UAV-based aerial images, e.g. in crop pests and disease identification, weed identification, plant counting or yield prediction. Recent studies combining UAV data and AI analysis are shown in Table 5. The integration of AI to data-processing and analysis also opens new perspectives for predictive analysis in agriculture. Furthermore, implementing 5G technology alongside with AI promises enhanced data transfer rates and real-time analytics, which will revolutionize the agricultural decision-making processes, that are currently mainly human based. Thus, agricultural decision support systems based on artificial intelligence decision models and UAV data are a promising research area for future development.

Table 5. Recent studies combining UAV data and AI analysis

Area of Utilization	Recent Studies	Description
Crop disease identification	Bouguettaya et al. (2022)	A survey on deep learning-based identification of crop diseases from UAV-based aerial images. The survey highlighted various UAV sensors (RGB, multispectral, hyperspectral, thermal) adopted to identify crop diseases. Different deep learning models were used to identify crop and plant diseases from aerial images were presented
Crop yield prediction	Fei et al. (2022)	A study focused on machine-learning algorithm analysing UAV-based multi-sensor data in order to predict yields in wheat
Weed detection	Catala-Roman et al. (2024)	An AI-based autonomous UAV swarm system for weed detection and spraying treatment

In summary, it is evident that AI plays a crucial role in the future direction of UAV technology development, opening new promising research areas for UAV autonomy, AI-driven UAVs and data analysis. For enhanced crop production, the greatest potential can be seen in UAV team deployment and integration to both manned and unmanned farm. Due to the agricultural operations realized in open field conditions, the quick transfer and intervention of machinery without damage to the soil and crop is important. This is opening the potential for UAVs in various areas, as their key advance over ground machinery is that no soil compaction is present. Soon, unmanned farms and systems are expected to become popular. For future UAV farm systems, it is expected that almost no tracks will be present in field caused by ground machinery, thus bringing the potential for larger arable area and higher yields. In this context, this will be crucial for future agricultural crop production, considering the increasing number of world population.

CONCLUSIONS

This literature review highlighted the importance of UAV technology in the transformation process of the agricultural sector. The aim of this review was to point out the future trends and importance of linking the technology of UAV with AI as one of the basic tools of the latest technological revolution Agriculture 5.0. The literature review focused on the utilization of UAV technology in precision agriculture, with the emphasis on the novelties, future trends and promising research areas.

UAVs have become integral to various applications in agriculture, where they enhance the efficiency and sustainability of the agricultural systems in the face of recent worldwide challenges such as climate change and food security. The effective utilization of UAVs in precision agriculture hinges on understanding both spatial and temporal variability in soil and crop characteristics. UAVs enhance the data acquisition and efficient monitoring by advanced sensing technologies.

In remote sensing operations, the novelties can be seen in precise data acquisition of both crops and soils characteristics, including the utilization of high-resolution RGB, multispectral and LiDAR sensors. Precise UAV collected data are expected to supplement the already existing datasets of satellite data. The importance of AI in the UAV data acquisition and post-processing is expected to rise, due to the emergence of AI data analysis tools and machine and deep learning algorithms.

The increasing integration of UAVs in precision agriculture also significantly affected the interventional applications of various inputs. The highest potential can be seen in precise, targeted applications of inputs, especially for spraying applications. However, the major challenges in this area are the regulatory and technological limitations in terms of safety and spraying quality. Due to the wide variation of design parameters among spraying UAVs, additional research is needed to make conclusive statements on overall safety of spraying UAVs. Regulatory disparities between countries worldwide are limiting the potential of UAVs in both remote sensing operations and interventional applications, thus harmonization efforts need to be implemented.

For other areas of UAV utilization, practical implementation can be identified in animal production too, especially in livestock production. UAVs play a crucial role in operations such as livestock counting, detection, animal position and monitoring of health status and behaviour, providing valuable data and enhancing the quality of animal production systems. For future directions of possible UAV utilizations, potential can be seen in the field of harvesting, transportation and implementation to indoor controlled farm environments.

Looking ahead, the future of UAVs is very promising. The linkage between UAV and AI is significantly enhancing various agricultural operations. Future trends can be identified in the promising research areas, such as the development of AI-driven UAVs, UAV swarms and enhanced UAV autonomy. Moreover, high potential can be seen in the integration of UAVs to unmanned farms. Further integration of AI alongside with IoT and 5G will provide fast and efficient data transfer and revolutionize the agricultural decision-making processes in real-time. Soon, the rise of fully automated farming systems that require minimal human intervention is expected.

In conclusion, UAVs are an integral part of the agricultural sector and are being positioned as irreplaceable tools for addressing the current agricultural challenges of the 21st century. Realizing the benefits of UAV and AI technology and the potential for future implementation areas, a close cooperation between farmers, industry and policymakers will be needed to overcome various regulatory, technical and socio-economic challenges. For a clear and healthy agricultural sector, it is crucial to find a balance between the technological possibilities of UAVs with AI, and the respect to data-privacy and socio-ethical considerations. Moving forward, both farmers and ordinary people will be influenced by the upcoming rapid advent of technology and must be ready to adapt to the incoming changes.

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Behera, K.B. & Varma, A. 2019. *Bioenergy for Sustainability and Security*. Springer International Publishing, Cham, pp. 1–377.

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