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Agroindustrial wastewater: recent advances and perspectives on the use of constructed wetlands

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Abstract. The treatment of wastewater generated by agro-industrial activities, such as dairy production and animal slaughter, represents a significant environmental challenge due to the complexity of pollutants. This study aimed to conduct a systematic literature review on recent advances in the application of constructed wetlands for the treatment of wastewater from agro-industrial activities. The bibliographic survey was carried out using the Scopus database, where the following keywords were used: 'Cattle wastewater', 'Fertigation', and 'Constructed Wetlands', covering the period from 2014 to 2024. After applying filters and inclusion/exclusion criteria, the search resulted in 82 articles. The distribution of publications over the analyzed period was examined, and a keyword co-occurrence map was created using the VOSviewer software. The results indicate that the use of constructed wetlands combined with techniques such as photobioreactors and anaerobic digestion demonstrates high efficiency in pollutant removal while enabling resource recovery, such as biogas and nutrients. The analysis of the co-occurrence map revealed interconnected themes, suggesting a convergence of studies around hybrid solutions for wastewater treatment in dairy production, livestock farming, and slaughterhouses. Finally, the study highlights the main challenges related to the removal of emerging contaminants and the spread of antimicrobial resistance, emphasizing the need for rigorous monitoring and the implementation of effective public policies to ensure environmental safety and the sustainable use of water resources.

Key words: agroindustrial wastewater, constructed wetlands, pollutant removal, water management, reuse.

INTRODUCTION

The treatment of wastewater from agro-industrial activities, such as dairy production and animal slaughter, is a significant environmental challenge due to the high load of organic, inorganic, and microbiological pollutants generated by these activities

(Michael et al., 2020; Queiroz et al., 2020; Mohamed et al., 2022; Souza et al., 2022; Jorge et al., 2023; Galindo Montero et al., 2024).

Various approaches have been investigated to improve pollutant removal efficiency and reduce associated environmental risks. Among them, biological treatments and constructed wetlands stand out for their efficiency and sustainability (Licata et al., 2021; Luz et al., 2022). Recent studies have shown that biological treatments can reduce physicochemical and microbiological parameters in dairy effluents (Jorge et al., 2023; Rajan, 2020), while constructed wetlands have demonstrated success in removing nutrients and antibiotic-resistant bacteria (Abdel-Mohsein et al., 2020; Rajan et al., 2020). Their functioning depends on factors such as vegetation and seasonal variation (Licata et al., 2021; Mahmoudi et al., 2024), which influence pollutant removal and biomass production. Additionally, irrigation with treated effluents can enhance crop productivity and reduce the need for synthetic fertilizers, as observed by Montemurro et al. (2017) in studies with fennel and lettuce.

These systems also enable resource recovery and reuse of treated water, contributing to sustainable agricultural practices (Kaszycki et al., 2021; Suh et al., 2024). Recent advances involve the integration of constructed wetlands with anaerobic digestion, photobioreactors, and the use of macrophytes, enhancing treatment performance and offering new alternatives for agro-industrial effluents (Ruales et al., 2024; Zhou et al., 2022).

However, despite these advances, significant gaps remain. Challenges such as the removal of emerging contaminants, efficiency under variable conditions, and the spread of antimicrobial resistance persist (Harada et al., 2016; Rahmani et al., 2020). Additionally, operational limitations in continuous bioreactors (Tonhato Junior et al., 2019) and climate-related efficiency variations demand further investigation and technological refinement.

A systematic review on the use of constructed wetlands for wastewater treatment is a valuable opportunity to understand the advances and challenges in this field. This type of analysis can help guide the development of more efficient and sustainable technologies, contributing to the protection of water resources and the reduction of the environmental impact caused by agro-industry (Van Tung et al., 2021; Mendieta-Pino et al., 2022; de Mendonça et al., 2022; Zhou et al., 2022). Furthermore, integrating these technologies with other strategies, such as anaerobic digestion and the use of biofilters, can enhance pollutant removal and improve treatment process efficiency.

In this context, the present study aims to conduct a systematic literature review of recent advances in the application of constructed wetlands for the treatment of wastewater from agro-industrial activities.

MATERIALS AND METHODS

The bibliographic survey was conducted using the Scopus database, where the following keywords were used along with Boolean operators: ‘Cattle wastewater’ AND ‘Fertigation’ OR ‘Constructed Wetlands’. Filters were applied for the period 2014 to 2024, language: English, and field of study: Engineering, resulting in 359 articles. Inclusion criteria were applied: studies that used constructed wetlands for the treatment of wastewater from dairies, cattle farms, slaughterhouses, livestock, treated wastewater, and cassava production. Exclusion criteria were also applied: studies that constructed wetlands used to treat other types of wastewaters not mentioned in the inclusion criteria, leading to a final selection of 82 articles.

RESULTS AND DISCUSSION

Annual Distribution of Publications

Over the analyzed period, the distribution of publications showed variations (Fig. 1). In 2014, no publications were recorded, followed by one publication in 2015. There was an increase in 2016 with six publications, a drop in 2017 with only one, and a slight rise in 2018 with three publications. The number of publications increased again in 2019, reaching eight, followed by a significant surge in 2020, with approximately 16 publications. In 2021, a decline was observed, bringing the number down to around nine.

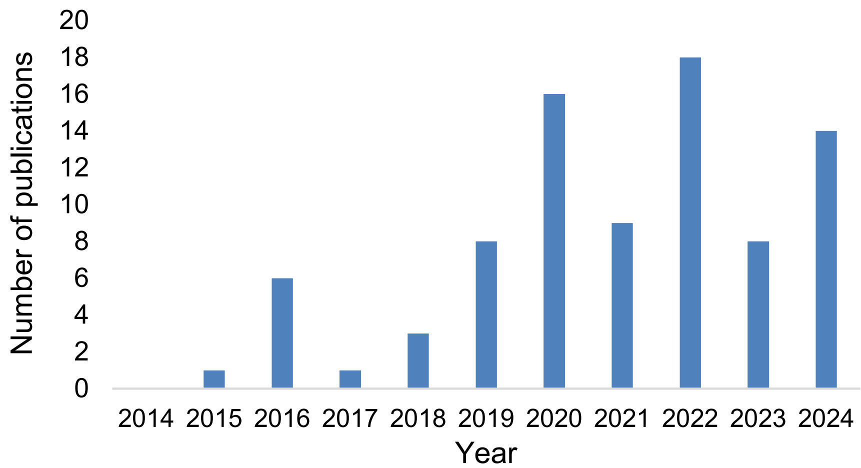

Figure 1. Distribution of publications over the analyzed period.

The year 2022 stood out as the period with the highest number of publications, reaching approximately 18. However, in 2023, the number dropped again to about eight. Finally, in 2024, there was a recovery, with the total number of publications rising to approximately 14. Overall, a peak was observed in 2022, followed by a decline in 2023 and a partial recovery in 2024.

Keyword and co-citation mapping: unveiling thematic clusters and intellectual structure

The keyword co-occurrence map was generated to identify the main thematic areas and analyze the relationships between the most frequently addressed topics in publications related to wastewater treatment.

In the present co-occurrence map, 99 items are displayed, organized into three clusters (Fig. 2). Each cluster represents a set of closely related terms: the first cluster (red) contains 39 items, the second (green) includes 30 items, and the third (blue) comprises 30 items. The most prominent keyword is 'wastewater treatment', which appears as a central term, highlighting its significance in the analyzed publications.

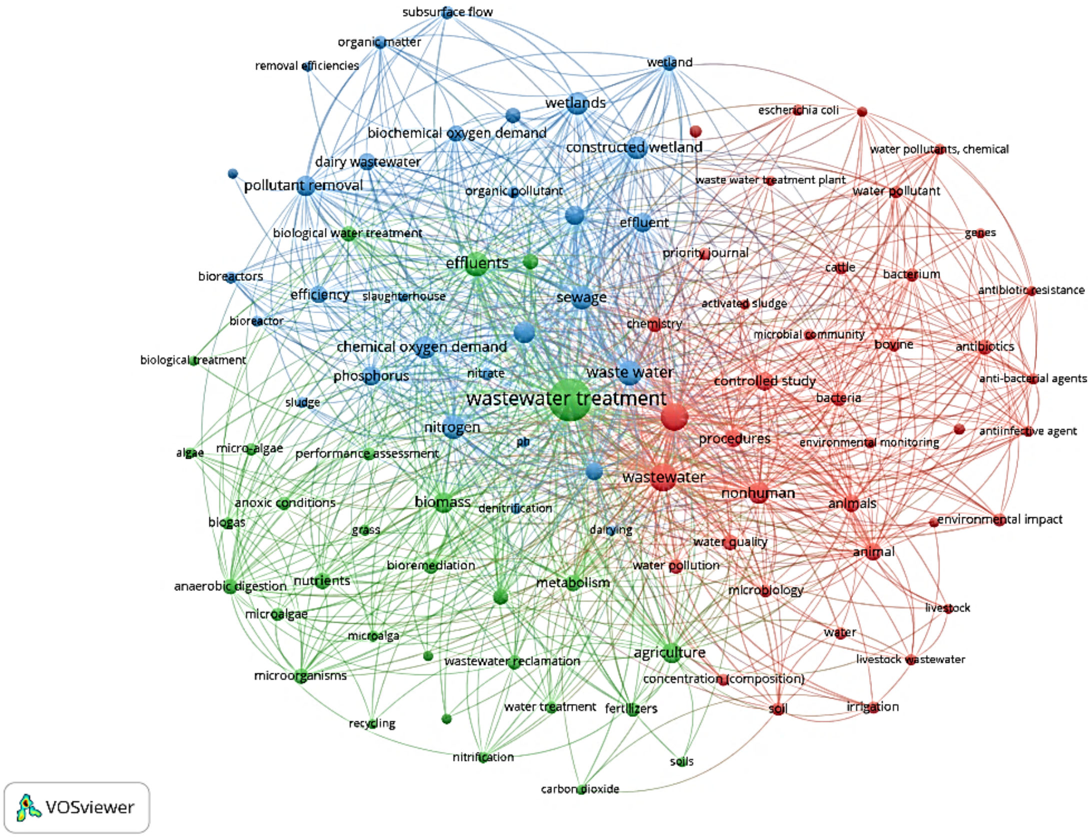

Figure 2. Keyword co-occurrence map.
Source: VOSviewer.

The red cluster is associated with topics related to contamination and conservation of water resources, including keywords such as ‘wastewater’, ‘water pollutant’, ‘water quality’, ‘animal’, ‘cattle’, ‘bovine’, ‘soil’, and ‘livestock wastewater.’ This cluster suggests a focus on studies addressing waste management from livestock activities and the impacts of pollution on soil and water quality. The green cluster, on the other hand, stands out for its focus on biological processes and sustainability, covering terms such as ‘biomass’, ‘biological treatment’, ‘fertilizers’, ‘wastewater treatment’, ‘microalgae’, ‘effluents’, and ‘microorganisms.’ This group suggests a research line aimed at using biotechnological processes for wastewater treatment and the generation of sustainable by-products, such as biomass and fertilizers. In the blue cluster, the most prominent term is ‘wastewater’, related to ‘biochemical oxygen demand’, ‘dairy wastewater’, ‘constructed wetlands’, ‘pollutant removal’, and ‘effluents.’ This cluster reflects studies exploring the use of treatment systems based on constructed wetlands for pollutant removal and effluent quality control. The co-occurrence map reveals, therefore, a comprehensive thematic distribution, with a central focus on ‘wastewater treatment’ and various complementary approaches, from livestock waste management and biological techniques to the implementation of sustainable treatment systems, such as constructed wetlands. This highlights the diversity of treatment strategies and the interrelationship between pollution, biological processes, and sustainability.

The co-citation map (Fig. 3) analysis reveals the intellectual structure of the field, showing 7 well-defined clusters that reflect the main thematic subareas The presence of central authors in each cluster indicates their influence, while the connections among clusters demonstrate the interdisciplinary nature and knowledge exchange within the area.

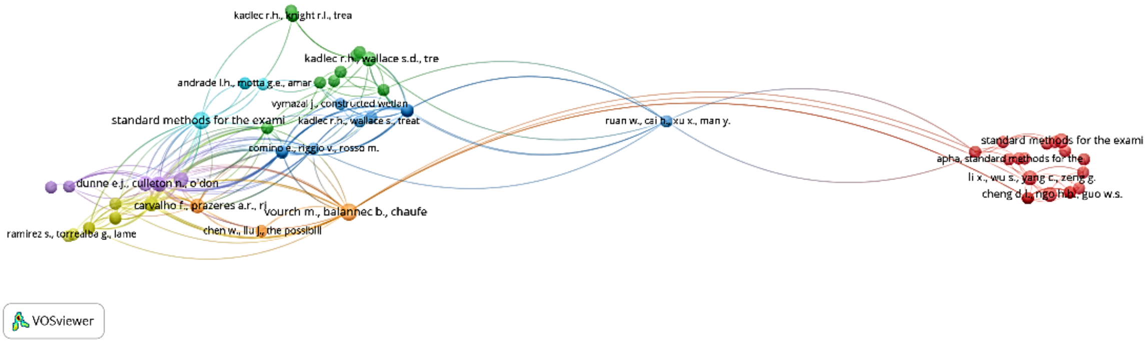

Figure 3. Co-citation map.
Source: VOSviewer.

Scientific Insights and Performance of Constructed Wetlands

Wastewater treatment covers a wide variety of sources, such as dairy, livestock, and slaughterhouse activities, and employs technologies such as constructed wetlands and hybrid systems. In the case of dairy effluents, research has shown that wetlands are highly efficient in removing pollutants, including nutrients, pathogenic bacteria, and organic matter, delivering good results even under different climatic and operational conditions (Licata et al., 2017; Rajan et al., 2020; Schierano et al., 2020; Licata et al., 2021; Mateo-Díaz et al., 2023).

The reuse of wastewater has emerged as a practical and sustainable alternative to address the increasing demand for water resources, especially during periods of water scarcity and in the face of climate change (Yerli et al., 2022; Phan et al., 2024; Ruales et al., 2024). In agriculture, this practice provides an efficient alternative, helping to reduce pressure on potable water sources. Additionally, it promotes the recovery of valuable nutrients, as demonstrated by Jorge et al. (2023) and Souza et al. (2022), who highlighted the use of treated wastewater to increase productivity and facilitate fertigation. However, caution is needed regarding potential impacts, such as increased CO_2 emissions from soil in irrigation systems (Yerli et al., 2022) and risks associated with antimicrobial resistance (Rahmani et al., 2020; Phan et al., 2024).

Regarding wastewater from livestock activities, innovative solutions such as bioenergy production through anaerobic digestion, combined with pathogen removal using wetlands, have gained prominence. These practices offer benefits not only to the environment but also to the economy by transforming waste into useful resources (Souza et al., 2022; Suh et al., 2024).

Constructed wetlands operate based on integrated mechanisms between plants, microorganisms, and substrates. Macrophytes play an essential role in water oxygenation, nutrient absorption, and biomass production (Hu et al., 2020; Lopes et al., 2020). Studies highlight the effectiveness of phytoremediation with species such as Tifton 85, which combine treatment efficiency with economic value generation (Kaszycki et al., 2021). Meanwhile, Abdel-Mohsein et al. (2020), Rajan et al. (2020), Mohamed et al. (2022), Jorge et al. (2023), and Mahmoudi et al. (2024) reported high efficiency in removing organic pollutants and antibiotic-resistant bacteria, confirming their applicability in effluents from cattle farms and dairies. Luz et al. (2022) and Thanh Hai et al. (2020) highlight the benefits of integrating wetlands with agricultural systems.

Furthermore, the presence of more complex contaminants, such as antibiotics and heavy metals, requires special attention. Solutions like phytoremediation and constructed wetlands have been identified as sustainable alternatives to efficiently mitigate these elements, contributing to environmental preservation and the safe reuse of water (Queiroz et al., 2020; Zhang et al., 2023; Khajah & Ahmed, 2024; Tao et al., 2024).

In industry, this approach also offers great opportunities. Anaerobic digestion of effluents, for example, can transform waste into renewable energy, such as methane, as pointed out by Sasidharan et al. (2023). The use of microalgae in wastewater treatment, as reported by Zhang et al. (2023) and Ruales et al. (2024), combines contaminant removal with nutrient recovery, creating a productive and sustainable cycle.

Pollutant removal occurs through processes such as biological degradation, adsorption, and chemical transformation. The combination of wetlands with anaerobic reactors and the use of biochar or microalgae has increased system efficiency, reducing greenhouse gas emissions and enhancing resource recovery (Van Tung et al., 2021; Zhang et al., 2023; Tao et al., 2024).

Furthermore, constructed wetlands exhibit high adaptability in different onfigurations such as surface flow, subsurface flow, and vertical or horizontal setups allowing for optimization based on site-specific conditions. Their efficiency is attributed to combined physical (sedimentation and filtration), chemical (adsorption, precipitation), and biological (microbial degradation and plant uptake) processes. Design variables, including hydraulic retention time, substrate type, plant species, and loading rates, play a crucial role in pollutant removal performance. Studies by Licata et al. (2021), Khajah and Ahmed (2024), and Mateo-Díaz et al. (2023) emphasize the importance of these parameters for the long-term success of CWs applied to dairy, livestock, and slaughterhouse effluents.

Studies have shown that constructed wetlands have high pollutant removal rates in agro-industrial effluents. For example, Schierano et al. (2020) reported removal efficiencies of 95% for BOD (Biochemical Oxygen Demand), 91% for total nitrogen, and 88% for total phosphorus in horizontal subsurface flow systems treated with dairy wastewater. Licata et al. (2021) observed that vegetated wetlands had removal of over 90% of fecal coliforms and a reduction of up to 87% in organic matter concentration. Mohamed et al. (2022) highlighted removal efficiencies of up to 93% of total suspended solids and 89% of residual antibiotics, when integrated into hybrid systems. These data demonstrate the potential of these technologies in the retention and transformation of several pollutants.

Advances, challenges, and future directions in wastewater treatment research

Despite the advances, there are still challenges that require in-depth investigation. These include the removal of emerging contaminants, efficiency under variable environmental conditions, seasonality and prevention of antimicrobial resistance (Harada et al., 2016; Rahmani et al., 2020).

There is a need for long-term monitoring, studies on economic feasibility, and the formulation of policies that encourage the adoption of sustainable technologies (Tonhato Junior et al., 2019; Van Tung et al., 2021; Zhou et al., 2022). The integration of systems with biochar, photobioreactors, and hybrid technologies emerges as a promising path to increase the efficiency and resilience of treatment systems.

In summary, research on wastewater treatment has undergone significant changes in recent years, with 2022 standing out as the year of highest scientific production (Fig. 1). This topic has attracted attention for its application in different types of effluents, such as those from dairies, livestock, and slaughterhouses (Prazeres et al., 2019; Schierano et al., 2020; Souza et al., 2022). Technologies such as constructed wetlands and hybrid systems have shown great potential in removing nutrients, organic matter, and more complex pollutants (Licata et al., 2017; Zhang et al., 2023; Suh et al., 2024). Additionally, methods like anaerobic digestion and phytoremediation emerge as viable alternatives from both environmental and economic perspectives (Ruales et al., 2024; Tao et al., 2024).

CONCLUSIONS

Advances in wastewater treatment reflect the need to combine technological innovation and sustainability. Technologies such as constructed wetlands and anaerobic reactors have already demonstrated promising results, but still need to be improved to address issues such as the presence of heavy metals and antibiotics. The integration of advanced solutions, such as the use of biochar and photobioreactors, can increase the efficiency of these systems. Furthermore, the reuse of these waters in agriculture and industry reinforces sustainable practices, promoting a cycle of environmental conservation. To consolidate these initiatives, it is essential to invest in continuous research, clear regulations and incentives that encourage the adoption of more sustainable approaches.

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