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Precision fertilisation technologies for berry plantation

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Abstract. Increased cost-effectiveness in crop production can be achieved by automating technological operations. This is also the case for berry cultivation in plantations. Starting any berry cultivation automation process should, quite naturally, begin with fertilisation, since this is the first technological operation to be carried out during the vegetation period and is a relatively simple one. The main task here is to apply the correct amount of fertiliser under the canopy of plants. Blueberry plantations that have been established on milled peat fields have plants that have been planted in parallel rows at a pre-designated interval. The fertilisation of plants must take place individually in the first years of their growth, so that each plant is fertilised separately. This form of fertilisation can be referred to as precision fertilisation. The aim of this paper was to provide an overview of the levels of technology now available when it comes to precision fertiliser equipment and to introduce the concept of a new precision-automated fertiliser unit, while also justifying the efficiency of using automated equipment. The automated fertiliser unit that is to be designed will be autonomous, will move unmanned through the plantation, and will include the necessary sub-systems for the precision fertilisation of individual plants, such as a plant detection system, a fertilising nozzle, a motion system and, additionally, a service station. On the basis of the results obtained, it can be argued that the use of an automated precision fertilisation unit increases productivity levels by approximately 2.25 times and decreases the specific fertiliser costs by approximately 8.4 times when compared with the use of a portable spot fertiliser.

Key words: berry plantation, agricultural robotics, precision fertilising, product design and development.

INTRODUCTION

The blueberry cultivation system consists of the following technological operations: soil preparation, planting, plantation maintenance, plant fertilisation, plant protection, harvesting, post-harvesting processing, and cutting back the plants or carrying out rejuvenation pruning (Starast et al., 2002; Olt et al., 2013; Zydlik et al., 2016¸ Retamales & Hancock, 2018).

These technological operations can be carried out either manually or using a machine (Scherm et al., 2010; Olt et al., 2013; Arak & Olt, 2014), with the latter method of cultivating blueberries being more productive and efficient than the former (Käis &

Olt, 2010; Takeda et al., 2017). Blueberry plantations have been established on mineral soils, but also on depleted peat milling fields (Peatland Ecology Research Group, 2009). Machinery has been developed that can carry out all of the technological operations that are involved in blueberry plantations that have been established on mineral soils.

Peat milling fields have a pH level and moisture regime that is suitable for blueberry cultivation (Noormets et al., 2003; Smagula & Litten, 2003; Arak et al., 2018); however, the ground used here has a low load-bearing capacity and, therefore, machinery with very low levels of specific pressure can be used and, unfortunately, such machinery has not been the centre of attention for larger machinery-building companies. A few smaller companies have produced the appropriate machinery though, and other units that potentially can be used in plantations that have been established on peat milling fields (Olt et al., 2013; Takeda, et al., 2017).

The main possibility offered in terms of reducing the unit cost of blueberry cultivation is by implementing machinery-based solutions. The use of machinery in blueberry cultivation sets out specific requirements for the plantation: the use of machinery is possible in continuously-maintained and pruned plantations; in order to ensure normal operations in terms of servicing and harvesting machinery, the plantation ground must be level and should remain level during use; service or technical roads must be established; machine harvesting requires the periodic pruning of old branches; first rejuvenation pruning is carried out between the eighth and tenth years of operations, and thereafter every three or four years.

The efficiency of machine cultivation around berry plants, including blueberries, can further be increased by using methods that involve precision cultivation (Chang et al., 2012) and by automating the technological operations that are involved in the process. In the implementation of precision cultivation, unmanned platforms (Dubbini et al., 2017; Grimstad et al., 2018) and field robots (Hayashi et al., 2010; 2014; Yamamoto et al., 2010; 2014) are increasingly being introduced into the process of carrying out the various technological operations.

Beginning the automation of blueberry cultivation from the point of fertilising the plantation is entirely reasonable when it comes to carrying out that process by using an automated fertiliser unit. With any berries, blueberries included, the fact that the availability of nutrients in the soil significantly affects the productivity of the plants is a factor that must be taken into account (Farooque et al., 2012; Chen et al., 2014). Average blueberry yield can go from 1.49 t ha^{-1} to 5.02 t ha^{-1} with the right fertilisation technics (Karlsons & Osvalde, 2019). Greater fertilisation norms (with nitrogen levels reaching up to 150 kg ha^{-1}) serve to significantly improve the growth of the plants and improve yields (Ehret et al., 2014), especially with soils that are low in nutrients (Starast et al., 2007; Paal et al., 2011). A strong positive relation has been found between the availability of nutrients and the vegetative parameters of the blueberry plant - in terms of its height and the total area of the leaves (Liet, 2017; Vainura, 2018).

However, fertilisation depends both upon the properties of a specific soil and the plant's age, which results in a specific norm for each fertiliser. From the point of view of the plant's age, the fact should be kept in mind that the root grows each year and this will result in a larger area to be fertilised. In the first year, the fertiliser should be spread across a smaller area of about 20×20 cm around the plant; at an age of between six to eight years, the area around the plant's roots have achieved their maximum dimensions (about 100×100 cm), and this also depends upon the density of the plantation: if the distance between plants in a row is 150 cm, then the area to be fertilised is 150×150 cm.

The aim of this research was to provide an overview of the current situation regarding fertilisers and their analogues, to introduce the concept of advanced fertiliser technology that will need to be developed, and to justify the effectiveness of using automated fertilisation equipment when compared to other well-known technological solutions.

MATERIALS AND METHODS

This work comprised the first phase of product development, the substance of which was to determine the current situation regarding technological equipment that can be used in fertiliser production, to define the available functionality, to create a concept, to search for and select constructive solutions, and to justify the effectiveness of those solutions (Ulrich & Eppinger, 2011).

The patent databases, Espacenet and World Intellectual Property Organization (WIPO), were used to determine the current situation. According to current regulations, the scope of the patent investigation was global and its depth covered a span of at least twenty years. In order to design the precision fertiliser technology for a berry plantation - in particular a blueberry plantation - it is necessary to define its core and individual functions, which are as follows:

1) in the blueberry plantation that has been created, the plants are arranged in rows with a set gap between them (between 1.0 m and 1.5 m, and possibly less or more), and therefore the automated fertiliser unit must move through the field, mainly in a straight line along the plant row;

2) the fertilisation of blueberry plants must take place individually in the first years of their growth, with each plant being fertilised separately according to the needs of the plant. It is expedient to apply spot fertilisation, with the fertiliser having to be spread around the plant and under its canopy (Hart et al., 2006);

3) the blueberry plants should be fertilised two or three times during the season by dosing the fertiliser at a rate of between 30–80 g for each plant (less in the first few years, more later) (Hart et al., 2006); therefore the automated fertilisation unit's dosing equipment should be set up to dispense the required amounts of fertiliser. Carpet fertilisation cannot be used in a blueberry plantation because it would allow weeds to flourish and that would unpredictably increase maintenance costs;

4) the automated fertilisation unit's functions must also include not only precise dosage of the fertiliser but also the identification of the plant's location (Milella et al., 2018; Brahmanage & Leung, 2019).

If the blueberry plants were located in one continuous row with a specific gap between them then it would be relatively easy to design an automated fertilisation unit - robot. But in real-life plantations, plant rows are not straight and the distance between plants varies. According to sources (Arak & Olt, 2020), deviations from the central axis of a plant row can reach up to ± 365 mm and the distance between plants - their spacing - can vary by 137.2 ± 166 cm on average in a plant row, being somewhere within the range of between 91.5 cm to 180.0 cm. The values for the transverse and longitudinal dimensions of the projection of the foliage vary widely between 5.0 cm and 48.0 cm, and between 4.0 cm to 44.0 cm respectively. For example, the mean height of two year-old plants is measured at 22.0 cm, but this also differs within a large range which can be anything between 6.0 cm and 39.0 cm. A type of fertiliser that adapts to these conditions can be described as a precision fertiliser, and a suitable stand-alone unit as a precision automated fertilisation unit.

The cost effectiveness levels in terms of berry cultivation can be determined through the specific cost of any technological operation as e_A (EUR ha^{-1}), which includes the fixed and variable costs involved in the operation as follows:

$$e_A = \frac{1}{W}(C_F + C_V), \tag{1}$$

where W – the fertilising unit's productivity levels; C_F – the fixed cost, € h^{-1}; C_V – the variable cost, € h^{-1}.
with the fixed cost C_F being expressed as follows:

$$C_F = \frac{1}{T}\left(C_f + C_a + C_h\right), \tag{2}$$

where T – the fertilising unit's seasonal load i.e. its total operating time during the season, h; C_f – the fertilising unit's depreciation, €; C_a – its battery's depreciation, €; C_h – its service station's depreciation, €.

Taking into account that

$$C_f = \frac{C_{fb} \cdot a_{fc}}{100}, C_a = \frac{C_{ab} \cdot a_{ac}}{100}, C_h = \frac{C_{sb} \cdot a_{sc}}{100}, \tag{3}$$

where C_{fb} – the carrying volume for the automated fertilising unit, €; C_{ab} – the cost of its battery (or batteries), €; C_{sb} – the carrying volume for its service station, €; a_{fc} – the depreciation rate of the automated fertilisation units, %; a_{ac} – the depreciation rate of its battery (or batteries), %; a_{sc} – the depreciation rate of its service station, %, we can express the fixed cost as follows:

$$C_F = \frac{1}{100T}\left(C_{fb} \cdot a_{fc} + C_{ab} \cdot a_{ac} + C_{sb} \cdot a_{sc}\right). \tag{4}$$

The variable cost C_V is expressed as:

$$C_V = \frac{C_m}{T} + C_e + C_w, \tag{5}$$

where C_m – the annual cost of servicing (involving maintenance and repairs) for the automated fertilising unit, €; C_e – the cost of electricity to recharge the battery, € (kWh)$^{-1}$; C_w – related labour costs (wages and taxes), € h^{-1}, whereas the specific cost C_e (€ (kWh)$^{-1}$) of electricity to charge the battery is calculated as follows:

$$C_e = Q_e \cdot (r_e + r_c + r_r + r_a) \tag{6}$$

where Q_e – the hourly electricity consumption rate (kWh) h^{-1}; r_e – the purchase price of electricity, € (kWh)$^{-1}$; r_c – the network fee, € (kWh)$^{-1}$; r_r – the renewable energy fee, € (kWh)$^{-1}$; r_e – the electricity excise duty, € (kWh)$^{-1}$; and labour costs C_w are calculated as follows:

$$C_w = M_c \cdot q_p \cdot k_p, \tag{7}$$

where M_c – the area of the plantation that is being fertilised by the automated fertilising unit or, in other words, the automated fertilising unit's productivity levels, ha h^{-1}; q_p – remuneration for the operator of a manually-operated fertilising unit in terms of fees to be paid for fertilising one hectare of the plantation, € ha^{-1} (or in the case of an automated fertilising unit being used, $q_p = 0$); k_p – the factor accounting for labour taxes; $k_p = 1.34$.

Given the relationships (5) – (7), we get the formula for calculating the variable cost as follows:

$$C_V = \frac{C_m}{T} + Q_e \cdot (r_e + r_c + r_r + r_a) + M_c \cdot q_p \cdot k_p. \quad (8)$$

The productivity area W_A (ha h^{-1}) for the precision automated fertilisation unit can be calculated as follows:

$$W_A = 0.36 \cdot v_k \cdot B_h, \quad (9)$$

where v_m – the average operating speed of the automated fertilisation unit, m s^{-1}; B_h – the operating width, m.

Considering that $v_m = s_f/(t_m + t_s)$ and the working width is equal to the row width $B_h = s_l$, the productivity area can be expressed as follows:

$$W_A = 0.36 \cdot \frac{s_f \cdot s_l}{t_m + t_s}, \quad (10)$$

where s_f – the distance between plants, ie. the ‘step’ between plants in a row, m; s_l – the row width, m; t_m – the time taken in moving from plant to plant; t_s – the time taken for standstills and/or dosing the fertiliser.

The operations of a working fertiliser are better characterised by shift productivity levels - its working day productivity levels $W_{A,d}$, which are expressed as follows:

$$W_{A,d} = 0.36 \cdot \frac{s_f \cdot s_l}{t_m + t_s} \cdot T_d \cdot \tau, \quad (11)$$

where T_d – the total length of a working day or of a single shift in the plantation, h; $_d = 8$ h; τ – the working time usage factor, whereas

$$\tau = \frac{T_e}{T_d} = \frac{T_e}{T_e + T_p + T_t + T_l + T_o}, \quad (12)$$

where T_e – the effective working time h of the fertilising unit, ie. the time involved in the fertilising unit moving along the plant row and fertilising the plants; T_p – the time taken to turn on the turning strip and to move from one work path to another; T_t – the time taken to move to the service point and to return to the work in progress; T_l – the time taken to fill up the fertiliser bunker and to set up the fertilising unit; T_o – the organisational time involved, including the time taken for short-term rests.

In this work, the cost effectiveness levels involved in the fertilisation of berry plants has been compared with that of manual fertilisation, with the use of a portable spot fertiliser and a precision automated fertilisation unit being taken as an example.

DESIGN AND DEVELOPMENT OF THE FERTILISING ROBOT

A determination of the current situation regarding fertiliser technology

A patent investigation revealed that, according to patent document CN209192086U, there exists an automated field unit which contains a frame, driving and rear wheels, a drive, and a work tool. A shortcoming of this already-available automated field unit is the fact that its drive is equipped with an internal combustion engine which generates noise, has a high purchase cost, emits carbon dioxide and other harmful chemical compounds into the atmosphere as a result of fuel combustion, and involves high levels of cost in terms of regular technical maintenance during its use. According to patent document CN108551783A, there currently exists an automated field unit that consists of a frame, driving and support wheels, a drive, and sowing and fertiliser tools. This unit is a mobile machine for row-based sowing of seeds and the application of fertilisers, and its main drawback is the fact that it sows seeds and fertilises along a set row patterns and is unable to react to deviations from that row. According to patent document CN109196995A, there is an extant automated fertiliser unit which contains a frame, a fertiliser tool, a transmission section, a control unit, and accessories. A shortcoming of this particular automated fertiliser unit is its lack of functionality. The main problem with those automated fertiliser units that can be found in a search through the available patent records is that they lack a plant recognition function.

According to document EE 01058U1, there exists a fertilising unit that has a precision dosing function, while also including a fertiliser bunker, a volume-based dosing module with a regulator and a drive, and a fertiliser line and dosing nozzle. This unit's dosing module is a volume-based dispenser which is connected to a drive that contains a control unit. The dispenser's drive unit is an electric drive which consists of a step motor which allows the fertiliser quantity to be set up and used as a precision fertiliser in a berry plantation, by means of dispensing the prescribed quantity of fertiliser individually to each plant. The main shortcoming of the fertilising unit described above is that it is a portable unit which is carried and operated manually, which means that its operating time per day is limited (to eight hours) and it is directly dependent upon the operator's work capacity.

Automating the fertilising process

The authors of this work aimed to be able to automate the fertilisation process in connection with blueberry plants, which consists of automating the fertilisation unit - making it autonomous and self-regulating. This fertilising unit will contain a fertiliser bunker that is rigidly attached to its frame by means of a structural grid, as well as possessing self-adjusting guide wheels, rear wheels, a dosing unit that is attached to the lower part of the fertiliser bunker and a fertiliser line that is connected to the dosing unit's upper section, a traction drive, a control unit for the fertilising unit as a whole, a sensor block, a precision fertilising tool, an onboard computer, and a battery. The automated fertilising unit's control unit (Fig. 1) contains a steering wheel drive which allows the unit to turn its steering wheels, a traction drive to ensure that the automated fertilising unit moves forwards, and a brake drive to stop it during the fertiliser dosing process. The automated unit has a wheeled chassis with two steering wheels and two rear wheels. Electric drives have been used for a steering wheel drive, a traction drive, a brake drive, and the dispensing nozzle's drive. The fertiliser line is connected to the dispenser by its upper end. The dispenser is a volume-based unit which is equipped with a regulator and is connected to a drive that contains a control unit in the form of a step motor.

The fertiliser line is a flexible, tubular element with a dosing nozzle at its lower end, and which is attached to a linear guide. The function of the linear guide is to move the dispensing nozzle in an oblique direction in relation to the fertilising unit's motion target.

The sensor block contains plant recognition cameras, an energy storage indicator, a navigation sensor, and a level-recognition sensor in the fertiliser bunker. The precision fertilising machine includes a plant detection camera, a dosing nozzle drive, a linear guide, and an automatic switch on the dosing unit. One plant detection camera which is designed to detect the location of a plant row is attached to the front end of the automated fertilising unit and another, designed to identify the plant to be fertilised, is placed near its precision fertilising unit.

The automated fertiliser unit's service system includes a remote database for data transmission, a digital twin and a service station containing a fertiliser tank which is equipped with a filling unit for the fertiliser unit's fertiliser bunker, a level sensor for the fertiliser tank, and a charging unit for charging the fertiliser unit's energy storage unit. Other units may also be operating within the service system of a berry plantation. Information on the functioning of the service system will be provided to the farmer or to the operator who is responsible for making decisions when it comes to controlling the automated fertilisation unit.

The service station contains a fertiliser tank that is equipped with a filling unit for the fertiliser unit's bunker, a level sensor for monitoring the fertiliser tank's level, and a charging unit for charging the fertiliser unit's energy storage battery. The filling unit for the fertiliser's bunker consists of a screw conveyor.

The automated fertiliser unit works as follows: the fertiliser bunker in the automated unit is filled with fertiliser at the service station and its energy storage unit is charged. The automated fertiliser unit, now fully prepared for fertilisation, will be directed from the service station to move along the rows of berry plants within the plantation and will move in a shuttling manner, progressing from plant to plant.

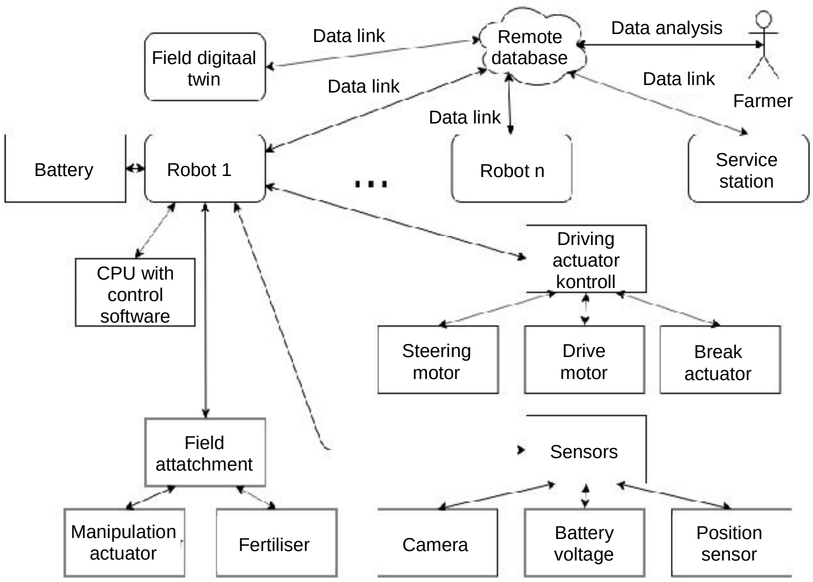

Figure 1. A block diagram showing the automated fertilising unit and its service system.

The automated fertilisation unit's service system is connected through a data communication relay to a remote database (Fig. 1), where the unit's main logs are kept and access to current data and calculation results is provided to other parties. The automated fertilisation unit and its maintenance station provide data uploads to the remote database and download instructions from the remote database. In addition, other robots can work within the berry plantation's system, with these also being coordinated through the remote database. Information on the operations of the service system is provided through the remote database to the farmer or to the responsible operator who is making the control decisions. The digital twin receives the input required for simulation from the remote database, in order to predict the need for maintenance and to allow for the digital reproduction of a deviation situation in a simulation environment. The automated fertilisation unit's sensor block provides feedback from the sensors to the onboard computer where data processing is carried out by the required software. On the basis of the processed data, the performance of assigned tasks is assessed and the necessary control effects are transmitted to the precision fertilising unit and to its control unit. The navigational sensor and the plant detection cameras are used to identify the position of the automated fertilisation unit within the plantation in relation both to the plant row and to the specific plant. Based on information received on the location of the automated fertilising unit, a sequence of activities is planned with the aim of fertilising the centre of the plant. From the image received from the plant camera, the angle is calculated between the plant row and the direction of the fertilising unit's movement, which is then attempted to be reduced by a correction impulse to the steering wheel drive. When the detected plant comes within the precision fertiliser unit's work area, the traction drive is stopped, the brake drive is applied, and the automated fertilisation unit is stopped while the plant detection camera is used to check that the dosing nozzle has reached the optimum location for fertiliser delivery, sending an impulse to the control drive for the dosing nozzle. The automatic dose switch is activated and fertiliser moves from the dosing unit through the fertiliser line to the dosing nozzle, where it drops to the designated spot when it reaches the ground. A transverse displacement device will move the dosing nozzle in a transverse direction compared to the automated fertilisation unit's direction of movement so that it can dispense the fertiliser to the intended location. After the fertilisation operation has been carried out, the traction drive is started and the brake drive releases the brake so that the automated fertilisation unit can move over to the location of the next plant. The plant fertilisation cycle will continue to be repeated until either the reading on the level sensor in the fertiliser bunker or the charge indicator on the energy storage unit falls below the set point; thereafter the automated fertilisation unit proceeds to the maintenance station, uploading to the maintenance station's remote database the location at which it stopped providing its intended service. At the maintenance station, the automated fertilisation unit stands still until its fertiliser bunker is filled with fertiliser and its battery has reached its intended level of charge or has been replaced. Technical maintenance can also be carried out on the automated fertilisation unit at the maintenance station if necessary. After leaving the service station, the automated fertilisation unit will return to its unfinished task or is directed by the remote database to start a new task.

In stand-alone driving, the automated fertilisation unit uses software algorithms to avoid obstacles, taking into account not only its own presence but that of other automated units within the plantation, based on information in the remote database. To be able to avoid random objects, the locations of the bodies are used as they are calculated from the image stream on the plant detection camera.

In addition, other robots can work in the berry plantation system, being coordinated through a remote database. Information on the operation of the system will be provided through the remote database to the farmer or to the responsible operator so that control decisions can be taken. The automated fertilisation unit's onboard computer checks for task execution based on feedback from the sensor block. The navigation sensor and the plant detection camera are used to detect the position of the automated fertilisation unit in the plantation in relation both to the plant row and to the plant. Based on information received on the location of the automated fertilisation unit and from the plant detection camera, a sequence of activities is planned with the aim of bringing the dosing nozzle to the plant so that the intended amount of fertiliser can be supplied. If the reading on the fertiliser bunker's level sensor or the energy storage unit's charge indicator falls below the set point, the automated fertilisation unit will head to the maintenance station. Once the required level for the fertiliser bunker and/or the charge level on the energy storage unit have been reached again, the automated fertilisation unit will return to its last location and continue any task that it has not yet completed.

The first prototype of the automated fertilisation unit has been built on the platform of an electric ATV Hecht 56150 (Fig. 2). The specifications for the automated fertilisation unit's prototype are given in Table 1.

Table 1. Technical specifications for the original prototype of the automated fertilisation unit

Parameter	Unit	Value
The unit's dimensions (l × w × h)	mm	1,450×1,020×960
The unit's weight	kg	120
Engine power	W	1,200
Batteries	Ah	20
Movement speed	km h^{-1}	40
Load-bearing capacity	kg	120
Working speed	km h^{-1}	1.8
Fertiliser bunker volume	L	20

Figure 2. The original prototype of the automated fertilisation unit.

Specific cost of spot fertilising operations

We compare the specific costs involved in spot fertilising with the use of three different technical means, namely fertilising:

1) with a bucket and a measuring shovel;
2) with a portable spot fertiliser;
3) with an automated precision fertilisation unit.

Based on the data provided in sources (Arak & Olt, 2020), the distance between plants in the spreadsheet calculations amounts to 1.4 m between rows, with the length of plant rows being 280 m. Each plant row contains 200 plants. In all cases the fertilisation rate was equal to 30 g per plant. The number of plants to be fertilised for different variants has been selected on the basis of an indicative daily norm (Table 2).

Table 2. Initial data for spreadsheet calculations

Indicator	Manual fertilising with a bucket and a measuring shovel	Portable contact spot fertiliser	Automated precision fertilisation unit
Number of plants to be fertilised, *N*	2,400	3,000	6,000
Length of the plant row *l*, m	280	280	280
Distance between plants in a row, s_f m	1.4	1.4	1.4
Spacing between plant rows, s_l m	1.4	1.4	1.4
Number of plants in a row, *n*	200	200	200
Number of plant rows	12	15	30
Volume of fertiliser bunker, L (kg)	10 (9)	20 (18)	100 (90)
Fertilisation norm, g plant^{-1}	30	30	30
Number of times the fertiliser bunker needs to be filled per day	8	5	2
Total weight of fertiliser given to plants, kg	72	90	180

Measurements and timings were taken for all of the usual operations, including the time taken to move from one plant to another, the standstill time, the time taken to administer the fertiliser, the time taken to turn to the next plant row at the end of the current plant row, the service time including time taken to fill the fertiliser bunker, and the time taken to replace the battery, as well as time for technologically-related matters, including the time taken to travel to the maintenance plant, such as the location at which the fertiliser bunker is to be filled, and the time taken to return to the work site. The organisational time, in terms of the operator's rest period which is ninety minutes a day. The data obtained was used to find an indicative time-use factor τ (Table 3).

Table 3. The technological characteristics of spot fertilising when using different technical means

Indicator	Manual fertilising with a bucket and a measuring shovel	Portable contact spot fertiliser	Automated precision fertilisation unit
Time taken to move from one plant to another along the row, t_m s	4.6	4.2	2.8
Time taken for standstills and to administer the fertiliser, t_s s	5.3	4.0	1.9
Time taken to turn to the next plant row, s	5.0	4.5	3.0
Effective operating time, T_e s	23,760	24,600	28,200
Total time taken to move from one plant row to another, T_p s	55	63	87
Technological time - total time taken to move to the service point or station and back, T_t s	2,255	1,590	160
Distance to the service point and back, m	2,480	1,740	330
Service time - total time to fill the fertiliser bunker and to replace the battery, T_l s	680	390	60
Organisational time (operator's rest time, coffee breaks, etc), T_s s	5,400	5,400	0
Time taken to fertilise plants, T_d s	32,150	32,043	28,507
Working time usage factor, τ	0.739	0.767	0.990
Potential productivity area, ha h^{-1}	0.071	0.086	0.150
Shift productivity, ha shift^{-1}	0.420	0.527	1.188
Productivity area, ha h^{-1}	0.052	0.066	0.149

RESULTS

Detailed results from the analysis are presented in Tables 3 and 4. Table 3 shows that if the fertiliser bunker is filled at one end of the field, this initial task takes a lot of time for a manual fertiliser to move to the service point and back to the working spot and to fill the fertiliser bunker. Working time is best used when working with an automated precision fertilisation unit. It is also important that any automated precision fertilisation unit does not require any rest periods or coffee breaks. It is noteworthy that in the case of using a manual fertiliser, a total of 2,400 plants take eight hours, 49 minutes, and 28 seconds to fertilise, or 13.27 seconds per plant. When using a portable spot fertiliser, a total of 3,000 plants can be fertilised in eight hours, 51 minutes, and three seconds, or 10.62 seconds per plant. An automated precision fertilisation unit fertilises a total of 6,000 plants in seven hours, 55 minutes, and seven seconds, or 4.75 seconds per plant.

Table 4. Indicators of economic efficiency for spot fertilising

Indicator	Manual fertilising with a bucket and a measuring shovel	Portable contact spot fertiliser	Automated precision fertilisation unit
Cost of equipment, EUR	12	729	8,900
Fertiliser unit's depreciation, %	–	10	10
Fertiliser unit's usage time, h	–	1,700	4,760
Fertiliser unit's standard depreciation, EUR h^{-1}	–	0.429	1.869
Cost of the service station, EUR	–	–	5100
Maintenance plant's depreciation, %	–	–	10
Maintenance plant's usage time, h	–	–	9200
Maintenance plant's standard depreciation, EUR h^{-1}	–	–	0.554
Electrical energy consumption, kWh $shift^{-1}$	–	–	4
Purchase price of electrical energy, EUR $(kWh)^{-1}$	–	–	0.0428
Transmission of electricity, EUR $(kWh)^{-1}$	–	–	0.0423
Renewable energy fee, EUR $(kWh)^{-1}$	–	–	0.0113
Electricity excise duty, EUR $(kWh)^{-1}$	–	–	0.001
Cost of electricity to charge the batteries, EUR h^{-1}			0.022
Labour costs, EUR h^{-1}	6.5	6.5	–
Labour costs, EUR h^{-1} (including taxes at 34.4%)	8.74	8.74	–
Fixed costs, EUR h^{-1}	≈ 0	0.429	2.423
Variable costs, EUR h^{-1}	8.74	8.74	0.049
Productivity area, ha h^{-1}	0.052	0.066	0.149
Specific operating cost, EUR ha^{-1}	168.00	138.92	16.59

As a result, during one shift of eight hours a total of 2,170 plants can be fertilised with a hand bucket and a measuring shovel, while 2,711 plants can be fertilised with a portable spot fertiliser unit, and 6,063 with an automated fertilisation unit. Therefore the automated fertilisation unit is 2.25 times more productive than the portable spot fertiliser unit. At this point it should be taken into account that the duration of a human working shift is eight hours a day, but only weather conditions can limit the working time of the automated fertilisation unit. The economic efficiency indicators for spot fertilisers are summarised in Table 4. The efficiency calculations have taken into account the fact that the maintenance station is also used for servicing a cleaning robot, which is why its usage time per year is longer than that of the automated fertilisation unit.

Table 4 shows that any mechanisation of the process produces greater levels of efficiency than does manual operation, and automation is even more efficient. It is characteristic that the application of precision fertiliser technology requires a significantly higher one-off investment than in other technological options, notably in terms of the acquisition of an automated fertilisation unit and a maintenance station, but the specific costs involved in the automated fertilisation unit are much lower than those involved with other technological options. Therefore, automated fertilisation unit will be more cost effective on larger plantations.

The data in Table 4 show that one automated precision fertilisation unit is suitable for serving plantations of at least 30 hectares, and taking 201 hours for a single fertilising operation, or approximately seventeen days or 2.5 weeks if working days are up to twelve hours long. The use of a portable local fertiliser is associated with a human factor, which allows for a maximum of eight hours for a shift and a maximum of 30 hectares for the same time (2.5 weeks) to be fertilised, using four units or working in shifts with two units. This calculation does not take into account the cost of the fertiliser, so the costs that are presented are not specific fertiliser costs, but reflect only the cost involved in carrying out the technological side of the operation.

CONCLUSIONS

The work has defined the current situation regarding the use of technological equipment for fertilising a berry plantation (the patent study itself), from which it was found that autonomous precision fertilisation in berry plantations is still something that has not been fully resolved in technological terms. This paper offers the concept of an automated precision fertilisation unit and its service system, providing definitions of the functions for such an automated unit, while selecting the robot platform, completing the original prototype, and providing an initial justification for the efficiency of using an automated precision fertilisation unit. On the basis of the results obtained, it can be argued that the use of an automated precision fertilisation unit increases productivity levels by approximately 2.25 times and decreases the specific fertiliser costs by approximately 8.4 times when compared with the use of a portable spot fertiliser. This will make it possible to reduce the realisation price for harvested crops and increase the competitiveness of berry farming. It should be added that the figures that have been obtained are provisional and still need to be checked under real production conditions.

In the subsequent R&D work, the automated precision fertilisation unit and its service system must be designed together with a modular maintenance station according to the concept. The parameters of the work tools must be optimised if necessary, work documentation must be prepared, the production technology must be prepared and made ready, the finished prototype must be manufactured, and a trial run must be carried out if necessary. The methodology to be resolved to be able to determine the individual fertiliser quantity for each plant. This would allow a saving to be made in terms of the cost of acquiring fertilisers, while preserving the balance between nutrients in the soil, reducing environmental pollution, and increasing the yield. Naturally, legal protection for the intellectual property resulting from the work must also be provided.

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