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Analysis of the Potato Vegetation Stages Based on the Dynamics of Water Consumption in the Closed Urban Vertical Farm with Automated Microclimate Control

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Abstract: One of the promising trends in modern agronomy is the development of automated closed urban vertical farms with controlled environmental conditions, which can improve dynamics of the crop vegetation process. In the frame of this work, the analysis of the vegetative stages of potato seed material (minitubers and microplants) grown in the conditions of the automated vertical farm was conducted. The study was performed at the vertical farm of the Federal Research Center "Fundamentals of Biotechnology" of the Russian Academy of Sciences by the analysis of water consumption dynamics. It was established that the 20-day reduction in the vegetative period of the vertical-farm-grown potatoes in comparison with the field-grown ones occurred due to the reduction in the final stage of vegetation (mass gain of newly formed tubers) under the minitubers planting. The same reduction occurred due to both final and initial vegetative stage (absence of tubers germination) under the planting of microplants. The obtained result shed new light on the vegetation dynamics of potato grown under controlled conditions of the urban vertical farms and demonstrated a possibility to perform the study of plant development process using automated diagnostics systems of vertical farms.

Keywords: urban vertical farming; potato; vegetation process; water consumption

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1. Introduction

One of the central directions of research in the field of agrotechnology is the creation of new methods for reducing the growing season of cultivated crops while maintaining and, if possible, increasing the quantity and quality of the crop. Currently, the main methods used for these purposes are based both on the direct impact on the cultivated plant and on the indirect impact by controlling environmental parameters. The first category of methods includes the breeding of early maturing high-yielding varieties [1], the use of inorganic [2] and organic fertilizers [3], as well as a decrease in the collateral effects of insecticides that negatively affect the course of vegetation [4]. The second category of methods includes control of the environmental parameters [5–7], such as ambient temperature, air humidity, CO_2 concentration, air exchange rate, watering conditions for plants, as well as the spectral composition of illumination [8], its intensity [9], the duration of the photoperiod [10], and the distribution of the light flux over the area occupied by the plants [11]. These methods also include the use of special technologies for growing and planting [12], as well as reducing the allelopathic influence during crop rotation [13]. At the same time, the mentioned methods aimed at managing environmental parameters are difficult to implement under the cultivation in the field conditions, thus these methods are usually used within the framework of closed urban vertical farms protected from the weather influence [14–16].

One of the promising trends in modern agronomy is the development of closed urban vertical farms with controlled microclimate parameters and irrigation regime [17]. These farms allow the production of food crops with low environmental impact and high economic efficiency as they guarantee a predictable level of yield throughout the year and reduce the cost of delivery to the final urban consumer. Growing plants under controlled conditions of urban vertical farms also allows reduction in the total vegetative period [18], as well as to test mathematical models of the influence of environmental parameters on the vegetation process [19–21] that determines both the practical and fundamental importance of closed urban vertical farms.

Speaking about the specific crops that can be cultivated in the conditions of closed vertical farms, the potato can be emphasized, since it is the one of the basic food crops, which is the fourth most actively cultivated food crop in the world after corn, wheat, and rice [22]. The practicability of potato production in closed urban vertical farms may seem to be a doubtful activity from an economic point of view. The common solutions in the area of urban vertical farms focused mainly on the cultivation of expensive crops—berries, edible flowers, rare greens, etc. The vertical farms that exist on the market today are not designed for growing popular crops, since it can be not economically profitable, and existing technologies pay off only for expensive crops.

However, the growth of healthy seed potatoes in the closed urban vertical farm of FRC Biotechnology RAS is completely cost-effective and allows crops growth with low margins. This healthy seed potato can be used by companies for the industrial-scale growth of high-quality potatoes and for growing on household plots. According to calculations, the cost of production (consisting of the cost of electricity, rent, and wages) of such potatoes is less than 50% of the market value of seed potato in the form of mini tubers. The payback of capital costs for the creation of such a farm with this technology is 2–3 years. Economic efficiency of this project is achieved by the sort-specific artificial lighting, high-density harvest (more than 10 times the productivity from 1 m^2 per year in comparison with the common field-based farms) and, last but not least, the reduction in the vegetative period in comparison with field-grown potatoes that allows obtaining up to six harvests per year.

Growing potatoes under controlled conditions of closed urban vertical farms allows both a reduction in the total growing season and an increase in its yield [23]. At the same time, the special conditions for the plants grown in the frame of urban closed vertical farms influence the dynamics of its vegetative stages. For example, even the use of different irrigation schemes in the frame of potato cultivation in controlled conditions modifies the moment of tuber formation start—thus, in [24] it was reported that potato tuberization occurred 6–8 days earlier under aeroponic cultivation than under hydroponic one. The diagnostics of plant vegetation dynamics can be based on the measurement of the nutrition exchange rate of the plant with the environment. One of the possible markers for this task is the soil water content, which can be easily measured in automated regime by the use of moisture sensors. Until now, moisture sensors have been widely used in the sphere of agronomy for the monitoring of the soil water content in automated irrigation [25], in the frame of investigations dedicated to the plant response to dry growth conditions [26], and for the comparison of different irrigation schemes [27]. However, to the best of our knowledge, there are no widely known investigations on the use of measured moisture dynamics for the analysis of plant vegetative stages, especially for the investigation of potato vegetation dynamics under cultivation in closed urban vertical farm.

In this regard, the purpose of this work was to analyze the dynamics of the vertical-farm-grown potato vegetative stages based on measurement of the dynamics of water consumption, determined via soil moisture sensors. The water consumption dynamics was determined by measurement of the substrate moisture throughout the entire growing season. The research was carried out on the experimental facility of the Federal Research Center "Fundamentals of Biotechnology" of the Russian Academy of Sciences, which is an urban closed vertical farm with controlled lighting, microclimate, and irrigation conditions. In this study, the analysis of the vegetation process of potatoes planted in the form of microplants and minitubers under controlled conditions of a closed urban vertical farm was carried out, and their vegetation process was compared with the vegetation process of field-grown potatoes.

The paper presents a description of the closed urban vertical farm conditions that were used for the potato cultivation, considers the methodology of water consumption determination, and provides a description of the obtained results and their discussion.

2. Materials and Methods

2.1. Description of the Growth Conditions

The structure of a part of the closed urban vertical farm of the Federal Research Center "Fundamentals of Biotechnology" of the Russian Academy of Sciences, involved in the study, is shown in Figure 1.

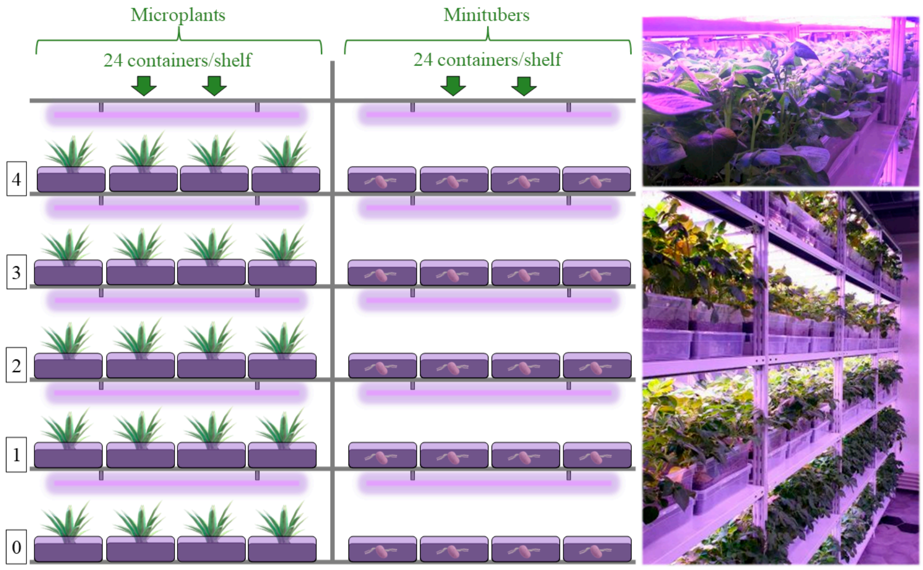

Figure 1. Structure of a part of the vertical farm of the Federal Research Center "Fundamentals of Biotechnology" of the Russian Academy of Sciences involved in the study.

The farm was located in a separate room with air temperature maintained at 18–20 °C. There were racks with 5 levels of shelves in the room. At each level, 24 individual containers were installed, in which a substrate with plants was placed (15 plants in a container). The total amount of containers with plants was 24 × 5 = 120 both for minitubers and microplants that allowed acquisition of statistical sampling for research. The substrate was a mixture of universal soil (composition: high-moor peat, lowland peat, sand, 6 limestone (dolomite) flour, complex mineral fertilizer with microelements (nitrogen—350 mg/kg; phosphorus—400 mg/kg; potassium—500 mg/kg; pH—6–7), neutralized peat (ash content—no more than 30%; humidity—no more than 65%, degree of decomposition of peat—no more than 35%; pH less than 5.5; composition: limestone (dolomite) flour), and expanded vermiculite (expanded fractionated vermiculite (EFV-4) in accordance with state standard 12865–67), with a total volume of 16 L. The volume ratio of the substrate components was 1:13:2 (peat/vermiculite/soil).

Above the containers was a system of controlled light-emitting diodes (LED) lighting with the possibility of programming the intensity, spectrum, and photoperiod of radiation, as well as automatic maintaining of lighting algorithms (spectral-time cycles). The duration of illumination period in the frame of this work was 14 h. The lighting conditions used in the work in the PAR area are presented in Table 1.

Table 1. Spectral distribution of illumination intensity in the PAR area.

PAR Intensity (400–700 nm), μmol/(m^2·s)			
Total Intensity	**Blue (400–500 nm)**	**Green (500–600 nm)**	**Red (600–700 nm)**
250 ± 25 (100%)	60 ± 6 (24%)	46 ± 4.6 (18%)	144 ± 14.4 (58%)

Diagnostics of the parameters of the vertical farm was carried out automatically using capacitive soil moisture sensors (calibration for air (0%) and tap water (100%), moisture measurement accuracy ± 3%), located in each of the containers, and a combined microclimate sensor that measured temperature and humidity of the air in the room, as well as the concentration of carbon dioxide CO_2. Data collection from these devices was carried out in real time with a step of 18 s, which, considering the duration of the full cycle of vegetation at the level of 90 days, provided the possibility of precise diagnostics of the vegetation process of grown plants. The collection and storage of sensor measurements in the database was carried out using the i-Sole web application [28]. As a part of the experiment, two forms of potato plants, namely, microplants and potato minitubers (variety "Innovator"), were planted in separate containers. The measurement of the soil moisture dynamics in each container made it possible to trace the dynamics of water consumption depending on the form of the plant.

2.2. Water Consumption Measurement

To determine the dynamics of water consumption, we used the dependence of substrate moisture on time, obtained using soil moisture sensors located in each container. Water consumption of plants was calculated as the average rate of decrease in substrate moisture between two successive irrigations (Figure 2).

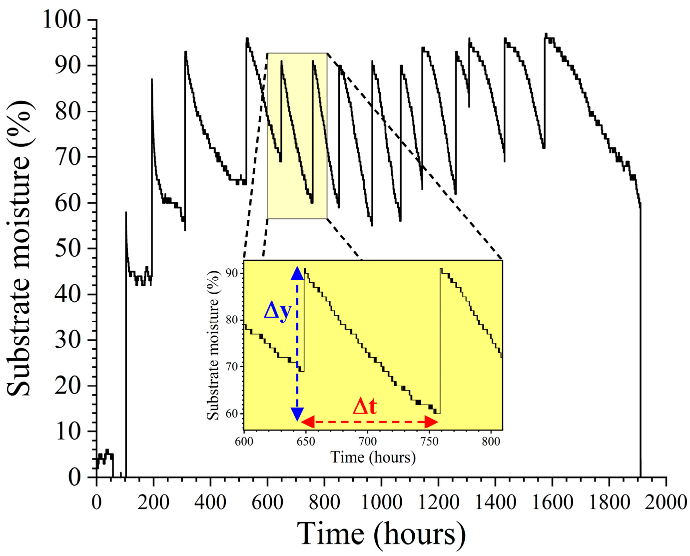

Figure 2. Determination of the plants water consumption. Each peak in the dependence of the substrate moisture on time corresponds to watering the plants in the container. Water consumption (%/hour) of plants was calculated as the average rate of substrate moisture drop between two successive waterings, i.e., $v = \Delta y/\Delta t$, where Δy is the drop in humidity over time Δt. The same pattern of soil moisture dependence on time is observed under the potato growth in the field conditions with artificial irrigation in arid area [26].

It should be noted that the dynamics of substrate moisture should also be influenced by the factor of evaporation of moisture into the surrounding air, in addition to the factor of water consumption by the plant. At the same time, since warmer and drier air accumulates in the upper part of the room, the evaporation of moisture from the substrate on the upper shelves should occur faster than on the lower shelves. Therefore, if evaporation has a significant effect on the dynamics of substrate moisture, there should be an increase in the rate of moisture drop ν with an increase in the shelf number. As it was experimentally determined, the moisture drop rate does not depend on the shelf number (see Figure 3), which allows us to conclude that there is no significant effect of moisture evaporation from the substrate on the dynamics of its moisture content.

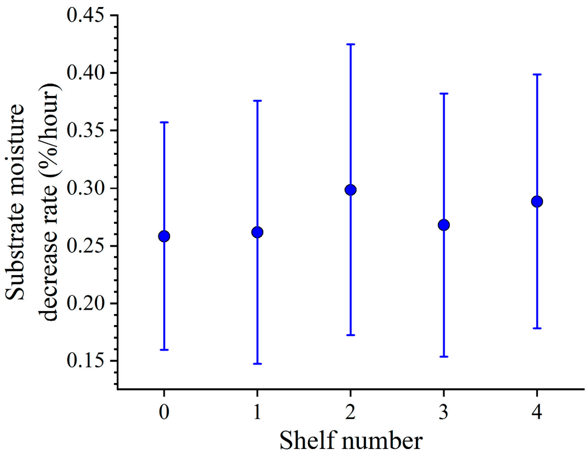

Figure 3. The plot of time- and container-averaged moisture decrease rate versus shelf number. As follows from this plot, the moisture decrease rate does not depend on the shelf number.

Thus, the dynamics of substrate moisture is completely determined by the water consumption of plants, which indicates the correctness of the described method for the water consumption determination.

3. Results and Discussion

Experimentally measured dynamics of water consumption of microplants and minitubers grown under controlled conditions of vertical farm is presented in Figure 4.

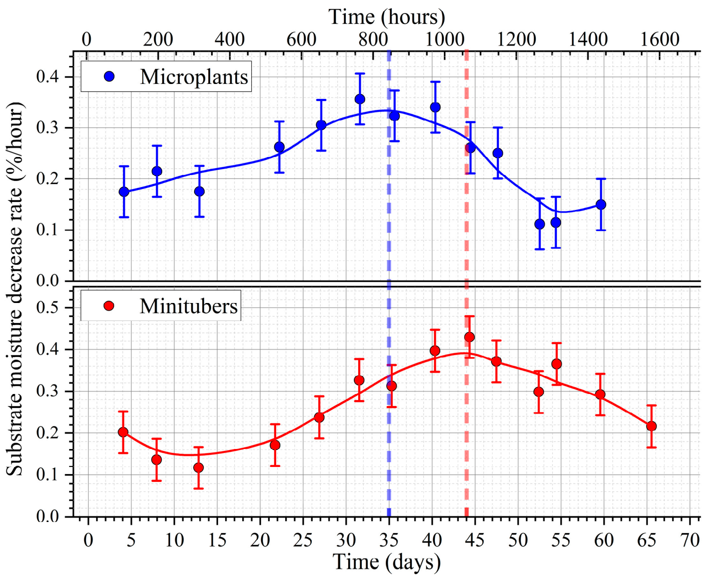

Figure 4. Dynamics of substrate moisture decrease rate for microplants and minitubers. Vertical dotted lines indicate the location of the extrema of the dependencies under consideration.

The dependencies in Figure 4 indicate the presence of distinct maxima, which have different time coordinate for microplants and minitubers. At the same time, the dynamics of the water consumption, including the water consumption maximum, indicates the vegetative stages of the plant. Thus, Figure 5 represents the water consumption dynamics of potato field-grown potato with marked vegetative stages (data from [29,30]). The data of the water consumption dynamics can be accessed in author's abstract for PhD thesis [29] (see [30]). This abstract has Table 2, which contains data of the day-averaged water consumption dynamics in the units of $m^3/(\text{ha}\cdot\text{day})$ for the field-grown potato of the "Romano" and "Nevsky" varieties. Data from this table (last column, case of sufficient water availability—Dir) are represented in Figures 5 and 6.

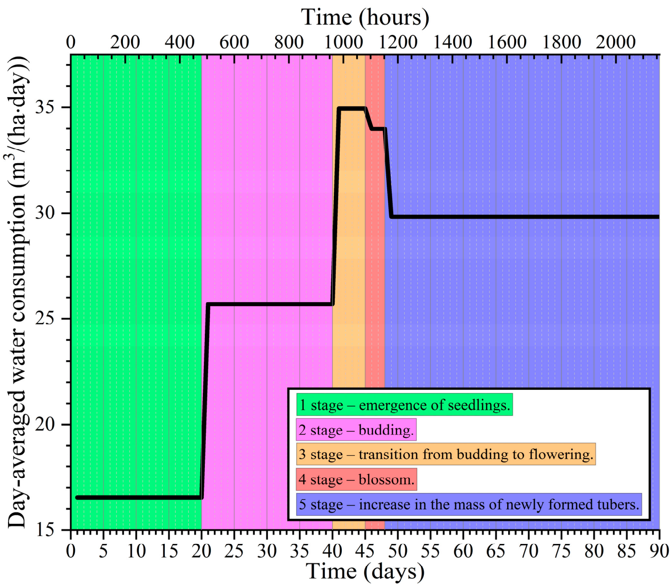

Figure 5. Dependence of the day-averaged water consumption of field-grown potatoes on time (according to data from [29]).

As it is indicated in Figure 5, the water consumption of the field-grown potato reaches its maximum 40–45 days after planting at the stage of transition from budding to flowering.

The dependencies in Figures 4 and 5 for field-grown and vertical-farm-grown potatoes can be compared. Thus, water consumption defined in units of $m^3/(\text{ha}\cdot\text{day})$ (Figure 5) can be directly compared with water consumption defined in units of $\%/\text{h}$ (Figure 4), since these units are linearly dependent and represent the same value that is the rate of water consumption by plants. Thus, the value of water consumption in Figure 5 for field-grown potato is:

$$S_1 = \frac{\Delta V_{\text{H}_2\text{O}}}{\Delta S \cdot \Delta t} \tag{1}$$

where ΔV_{H_2O} is the volume of water consumed by plants over a period Δt (=day) on the unit of field ΔS, which gives the units $m^3/(\text{ha}\cdot\text{day})$. The value of water consumption in Figure 5 for vertical-farm-grown potato, obtained from experimentally measured data, is the value:

$$S_2 = \frac{\eta}{\Delta S \cdot \Delta t} = \frac{m_{H_2O}}{m_{max}} \cdot \frac{1}{\Delta S \cdot \Delta t} = \frac{\rho_{H_2O}}{m_{max}} \cdot \frac{\Delta V_{H_2O}}{\Delta S \cdot \Delta t} = \frac{\rho_{H_2O}}{m_{max}} \cdot S_1 \tag{2}$$

where ΔV_{H_2O} is the volume of water consumed by plants over a period Δt (=hour) on the area of one container ΔS, η is a relative moisture level of a soil, m_{H_2O} is a mass of water consumed by the plants, m_{max} is the maximal mass of water in the soil under the given temperature, and ρ_{H_2O} is a water density. Thus, as it is indicated by expressions (1) and (2), the units of $m^3/(\text{ha}\cdot\text{day})$ is linearly related to the units of $\%/\text{hour}$, which indicates the equivalence of determining the value of water consumption using both units.

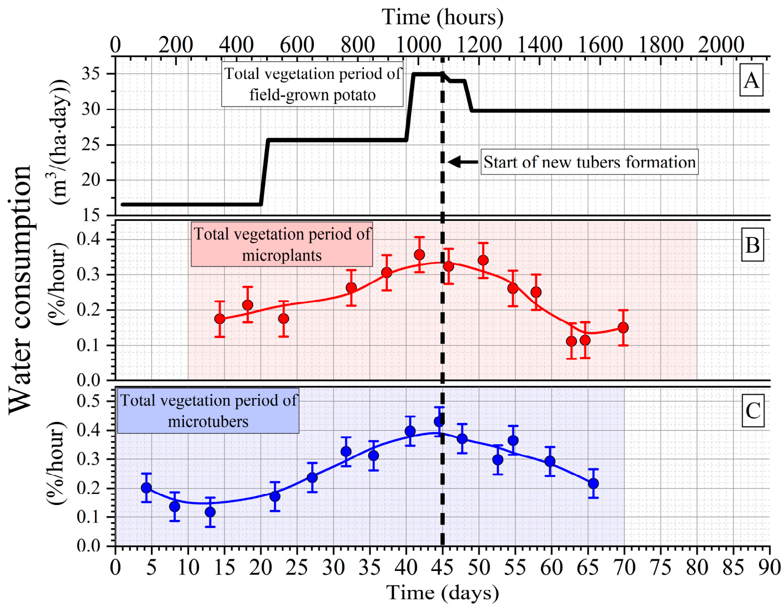

Figure 6. Dependencies of water consumption on time centered relative to the maxima, which correspond to the start of the new tubers formation process. (**A**) Water consumption of the field-grown potato (data from [29]). (**B**) Water consumption of the vertical-farm-grown potato planted in the form of microplants. (**C**) Water consumption of the vertical-farm-grown potato planted in the form of minitubers. Time axis is scaled from 0 to 90 days, i.e., the total vegetative period of the field-grown potato. The full vegetative period of microplants is highlighted in red, and the full vegetative period of minitubers is highlighted in blue.

The dependence of plant water consumption on time is one-to-one related to the dynamics of vegetative stages. Therefore, the measurement of dynamics of water consumption directly provides information about the dynamics of vegetative stages. Factors such as climate conditions, nutrition, etc., will affect the dynamics of vegetation and, as a result, the dynamics of water consumption. This resulting difference in vegetation dynamics between the field- and vertical-farm-grown potato is at the focus of investigation in this work. Thus, by comparison of the water consumption dynamics of the field- and vertical-farm-frown potato, it is possible to compare the dynamics of the vegetative stages in these cases. The reasons for the differences in this dynamics are caused by the differences in the mentioned factors.

Since in the frame of the current investigation the vertical-farm-grown potato of "Innovator" variety and field-grown potato of the "Romano" and "Nevsky" varieties were compared, another question that should be discussed is the varietal specificity of the reaction of plants to environmental conditions. Here, it should be mentioned that different potato varieties go through the same phases of development, which mutually determine the amount of water consumption at each time during the growing period. Therefore, tracking the dynamics of water consumption can be used to determine the stages of vegetation for any potato variety. In the current investigation, the varieties "Innovator", "Romano", and "Nevsky" are compared, which have approximately the same (80–90 days) ripening period in the field conditions, which determines the correctness of the conducted comparison between these varieties in terms of the dynamics of the vegetative stages.

As it was mentioned above, Figure 5 indicates that the maximum water consumption of potatoes occurs at the stage of transition from budding to flowering accompanied by the beginning of tuber formation, which is explained by starch synthesis and water accumulation in the formed tubers [31,32]. Based on this fact, it can be concluded that when potatoes are grown under controlled conditions of vertical farms, the beginning of tuber formation occurs on ≈35 days in the case of microplants planting and on ≈45 days in case of minitubers planting (Figure 4). At the same time, the full growing period lasts

70 days when growing microplants and minitubers under controlled conditions of urban vertical farms (Figure 4) and 90 days in the case of growing potatoes in the field conditions (Figure 5). The discussed dependencies of water consumption allowed determination of the stages at which the total growing season is reduced by 20 days in the case of vertical-farm-grown microplants and mini-tubers compared to field-grown potato. For this purpose, Figure 6 shows the dependencies of water consumption on time centered relative to the maxima of dependencies.

As it is indicated by Figure 6A,C, the full growing season of minitubers germinated under controlled conditions of urban vertical farm is reduced compared to the growing season of field-grown potatoes, due to a 20 day decrease in the duration of the final stage of vegetation, i.e., the mass gain of newly formed tubers after their formation. At the same time, in the case of vertical-farm-grown microplants, the total 20 days reduction occurs due to the initial stage of vegetation (10 days) and the final stage (10 days, see Figure 6A,B). The reduction in the initial stage of vegetation in the case of microplants is associated with the absence of the stage of germination of initial tubers, which are absent in case of microplants planting.

This behavior of water consumption in the case of microplants and minitubers can be explained as follows. Due to the absence of initial tubers, in which starch and water are stored as the main nutrients, by the time the formation of new tubers begins, microplants have less nutrients than minitubers, as evidenced by the different number of irrigations in both cases up to the beginning of the stage of new tubers formation. Thus, in Figure 6B,C, up to the line at 45 days, there are six irrigations in the case of microplants and nine irrigations in the case of minitubers. In accordance with this, a different amount of water was absorbed by this moment (45 days) by microplants and minitubers. Thus, the absorbed amount of water t is ≈200% in the case of microplants and ≈240% in the case of minitubers, which was calculated as integrals of dependencies in Figure 6B,C in the range 0–45 days.

Due to the small amount of nutrients stored by the time of new tubers formation, in the case of microplants, this stage lasts 10 days longer than in the case of minitubers (Figure 6B,C). At the same time, the total amount of water consumed at this stage turns out to be the same for both microplants and minitubers (≈175%, calculated as the integrals of dependencies in Figure 6B,C in the range 45–80 days), while the average rate of water consumption at this stage turns out to be lower in the case of microplants (≈0.2%/h) than in the case of minitubers (≈0.3%/h). An increase in the duration of the tuber formation stage in the case of microplants allows the plant to compensate for the small amount of nutrients accumulated by the time the stage of new tubers formation begins. Due to such compensation, the yield of microplants, as was established in the framework of this study, is approximately the same as the yield of minitubers: ≈25.4 kg and ≈26.2 kg from all five shelves, respectively. At the same time, due to the lower rate of tuber mass gain in the case of microplants, as evidenced by the values of the average water consumption rate above, newly formed tubers have, on average, two times less mass in the case of microplants compared to the case of minitubers—32 g and 63 g, respectively.

Thus, in comparison with the field-grown potato, the reduction in the total vegetative period of the vertical-farm-grown potato in the forms of microplants and minitubers occurs due to the different vegetative stages. In the case of minitubers, the 20-day reduction is the consequence of decrease in the final stage of new tubers mass gain, while, in the case of microplants, the 20 day reduction is caused by the 10 days decrease due to the absence of the of the initial tubers germination stage and 10 day decrease in the final stage of new tubers mass gain. This difference in the duration of vegetative stages of minitubers and microplants results in the smaller mass of newly formed tubers in case of microplants planting in comparison with the minitubers planting.

Additionally, it can be mentioned that the similar pattern of water consumption dependence on time (Figure 4) was reproduced in dependence of recommended levels of soil moisture for potato cultivation on vegetative stages (see Figure 2 in [33–35]). As it was indicated, the recommended moisture level reached its maximum at the stage of tubers formation. This fact directly correlates with the conducted analysis above, since the higher water consumption rate at the specific vegetative stage and the higher amount of water should present in the soil in order to provide the sufficient water supply for plant at this stage. Thus, the result of the conducted analysis was additionally strengthened by the previously published works.

In the frame of this research, the plant appearance change was observed during the vegetative period, and it was synchronized with the water consumption dynamics in accordance with the stages indicated in Figures 5 and 6. The plant appearance change also can be used for the monitoring of the vegetative stages dynamics. However, the use of water consumption measurement for the monitoring of the vegetation dynamics made sense as an alternative approach for the investigation of vegetation dynamics. The benefit of this approach was its potential for automatization: in order to measure the water consumption dynamics, it was only required to use a soil humidity sensor, while, for the automated control of plant appearance, it was required to use cameras together with the sophisticated image processing algorithm based on the use of neural networks. Thus, the described results demonstrated the measurement of water consumption dynamics to be relevant method for the monitoring of plant vegetation dynamics.

4. Conclusions

For the first time, to the best of our knowledge, an analysis of vertical-farm-grown potato vegetation process, based on measured water consumption dynamics, was carried out. This analysis made it possible to compare the vegetative stages of potato planted in the form of microplants and minitubers in the urban vertical farm with the ones of the field-grown potato. As a result of this comparison, it was found that the reduction in the total vegetative period by 20 days in the case of vertical-farm-grown potato, compared with the case of field-grown potato, occurred due to a reduction in the final stage (mass gain of newly formed tubers) under the minitubers planting, and due to the reduction in the final stage (by 10 days, the mass gain of newly formed tubers) and the absence of the initial stage (10 days, germination of tubers) in the case of microplants planting. The difference in the vegetative stage's dynamics of the microplants and minitubers led to the two times smaller mass of newly formed tubers in the case of microplants planting in comparison with the minitubers planting.

The obtained results clearly demonstrated that monitoring of the dynamics of plants water consumption could be used to analyze the vegetation process. The demonstrated analysis makes a contribution to the area of analytical methods in agricultural science. The future work based on the obtained results can be directed to the practical area. Thus, measuring the dynamics of water consumption of plants in a real-time regime could be used as a tool for diagnostics of the vegetation process, which could make it possible to quickly make decisions about changing the controlled parameters that affect the vegetation process, as well as predict the yield of the cultivated crop. This approach can be used both when growing plants under controlled conditions on an urban vertical farm and when growing plants in the field conditions using, in particular, a distributed network of measurement devices that transmit measurement results to a single storage device [36] or single mobile sensor moving on the field along the optimal trajectory [37].

Separately, it should be noted that use of the system for collecting data and monitoring microclimate parameters in the rooms of vertical farm created the prerequisites for the formation of new directions for studying the accelerated vegetation of plant crops with a given productivity. Moreover, it can be expected that under the development of adaptive microclimate control systems the modern artificial intelligence technologies and methods for intensive data flow analysis [38,39] will be of particular importance.

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