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Leachate Tables as a Tool for Monitoring Changes in Physical and Chemical Parameters of the Peat Substrate in the Cells of Nursery Containers

Michał Jasik [1,*], Mariusz Kormanek [2], Karolina Staszel-Szlachta [1] and Stanisław Małek [1]

[1] Department of Ecology and Silviculture, Faculty of Forestry, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland; karolina.staszel@urk.edu.pl (K.S.-S.); stanislaw.malek@urk.edu.pl (S.M.)
[2] Department of Forest Utilization, Engineering and Forest Techniques, Faculty of Forestry, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland; mariusz.kormanek@urk.edu.pl
* Correspondence: michal.jasik@urk.edu.pl

Abstract: Measuring the physical and chemical parameters of substrates in the cells of nursery containers during production is difficult. Monitoring these parameters, however, is required for optimizing the use of substrates and their components in nursery production, specifically important in the progressive reduction in the use of peat. A new solution—leachate tables—for those studies is presented. The leachate tables enable the collection of liquid samples draining from individual cells in nursery containers during long-term irrigation and fertilization. During our 2-month-long experiment, changes in the physical and chemical parameters of the substrate were analyzed, as well as the process of accumulation of elements fed to the substrate via fertilizer and irrigation water. It was found that, due to the different cell volumes, filling the containers with the substrate under the same parameters of vibration and initial moisture resulted in different fractions of the substrate ending up inside the cells. In the smaller cells, the larger diameter fraction was dominant, and in the larger cells, the smaller fraction was dominant. This may have influenced the differences in air and water capacity of the substrate in cells of different volumes and confirmed the need for the selection of individual vibration parameters for the containers. In addition, over time, the granulometric composition of the substrate in the containers changed. Along with the systematic administration of elements via fertilization from the sprinkler ramp, their leachate content increased as a result of increased leaching from the substrate. With time, the physical parameters of the substrate in the cells stabilized, which may have affected the accumulation and leaching of elements during irrigation and fertilization.

Keywords: container nursery; peat substrate; element accumulation; particle leaching

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1. Introduction

Peat is one of the components most often used for production in container nurseries [1,2]. It is estimated that, in Europe, peat is the basis of up to 90% of nursery substrates [3]. Other materials used as additives (up to 50%) to peat include sawdust, compost, coconut fiber, perlite, vermiculite, and dolomite. The increased use of peat is leading to the loss of raw materials and valuable habitats as a result of wetland drainage. It is therefore important that the use of existing peat resources is as optimal as possible and that understanding its characteristics could be used to partially or completely eliminate this material from nursery production [4–6]. Alternative substrates that could replace this material in the future (apart from those already indicated) are organic waste in the form of sewage sludge, tree bark, or post-clearing residues [3]. In the case of nursery substrates, which are usually placed in very small cell spaces in containers with volumes of 50 to 350 cm^3, the physical and chemical properties of the substrate are important [7,8].

The physical parameters of the substrate In the container are of vital importance because they affect the quantity and quality of the seedlings obtained [9]. The key here is the optimal circulation of air and water in the substrate, which depends on several factors, such as the share of pores, particle size distribution, specific and volumetric density, and the shape and volume of the container cell [10]. According to Benito et al. [11], the texture of the substrate best suited to growing seedlings has a granulometric fraction in the range of 0.25 to 2.5 mm, while the appropriate amount of oxygen and water accumulated in the substrate is ensured by high overall porosity in a range of 50 to 80% [12]. The most favorable parameters for peat–perlite substrates, according to the majority of the literature, include a general porosity of >70% and up to 93% of the volume, a total water capacity of up to 73% of the volume, and 20%–48% of the volume available for the plants, an air capacity of 20%–30% volume, and a wet weight of 864 kg m^{-3} [1,13–15]. The main problem that occurs during seedling cultivation in containers is the control and maintenance of these recommended ranges for the physical parameters due to the methodological problems associated with their determination [7,8,16,17]. Imported sphagnum-rich peat is mainly used in container production in Poland. It is characterized by its high porosity and water-holding capacity, as well as its sterility and low mineral content, which facilitates the determination of fertilization doses [1]. Inappropriate physical parameters of the substrate are difficult to correct; the main problem is air capacity being too low or too high, which is related to substrate compaction [18–20]. The degree of compaction and subsidence of the substrate in the container cells is influenced by its granulometric composition. The larger the components making up the substrate, the more diverse the bulk density of the components and the more intensive the irrigation, leading to greater compaction and subsidence of the substrate. With the passage of time, there is also a movement of fine substrate particles from the upper to lower levels of the cell alongside the decomposition of organic matter with the simultaneous impact of growing roots, all of which cause the substrate to compact, albeit at the same time increasing its permeability, which facilitates the diffusion of gases [18,21–25].

The volume and frequency of water supplied during artificial sprinkling are of great importance. These strictly depend on the air and water capacity of the substrate and the thermal conditions of the plant environment [26–28]. In a typical container, a growing plant can take up all the available water in 48 h. After intensive irrigation, the substrate is soaked mainly in the lower part, with the roots growing in this zone functioning without air until the plant absorbs the water or drains by gravity, which creates air pockets. If the substrate is irrigated with small doses, all the water may remain in the upper part of the cell, not reaching the lower part, which remains dry [29–32]. The amount of water that reaches the substrate is also reduced by the growing plants and interception by the assimilation apparatus [33]. With a dry substrate, the salt concentration in the soil solution can increase to high levels, and as a result of drainage, key elements, such as nitrogen (N) and potassium (K), can be leached out of the container. If these are not successfully replenished during fertilization, there will be a deficit in the substrate [15].

The chemical properties are also key in composing nursery substrates because they affect plant growth and nutrition. Depending on the availability of basic nutrients, they can act as a source or cause the loss of some nutrients [34]. As a rule, an organic substrate characterized by a high pH and cation exchange capacity, with a high C to N ratio, can have a detrimental effect on N availability [35]. Therefore, it is important to properly stabilize the substrate and ensure the appropriate pH values and electrical conductivity for plant growth [35,36].

The organic substrate can partially replace chemical fertilization, affecting the enzymatic activity of the soil and counteracting the negative effects of over-fertilization [37]. Particular attention needs to be paid to high pH values, high electrical conductivity and cation exchange capacity, as well as high contents of nutrients crucial for seedling development [35,38]. Undoubtedly, when analyzing currently used substrates and composing

a viable alternative, it is important to take into account both the chemical and physical properties to ensure good-quality planting materials.

The measurement of parameters and the determination of changes in the physical and chemical characteristics of substrates in the cells of containers during the production of seedlings in a forest nursery are difficult. This is mainly due to changing environmental conditions, which cannot be controlled, such as rainfall, temperature, sunlight, or wind. However, the volume of the available substrate is controlled, determined by the volume and shape of the container used, the amount of water and fertilizer fed to the cell by sprinkler systems, and the amount of fertilizer applied to the soil.

During nursery production, the growing seedlings themselves modify the physical and chemical parameters of the substrate. This growth interferes with the correct determination of the changes occurring in these parameters in the substrate, especially in the context of leaching and the accumulation of elements. Consequently, we addressed this problem in the experiment described here by developing a new leachate table that could enable the study of changes in the physical and chemical parameters of the substrate in nursery containers, be used in tandem with thermal parameter control, and have strict control over irrigation, fertilization, and lighting. The experiment was carried out on a peat–perlite substrate commonly used in container nurseries in Poland. Due to the consent of some EU Member States to reduce peat consumption [39–43] and because of upcoming restrictions on the availability of this material [44]—mostly imported into Poland and some other countries [45,46]—there is an urgent need to optimize its use or, in the near future, to find a material/materials to replace it either partially or completely. To achieve that, it is important to be able to sample the liquid seeping through the substrate (both with and without growing plants) during times of irrigation, fertilization, or chemical supply. Our technical solution makes this possible.

The tested research hypotheses assumed that, during long-term irrigation and fertilization, (a) the basic physical parameters of the substrate do not change, (b) the chemical parameters of the substrate do not change, and (c) the liquid fertilizer applied to the substrate does not accumulate in the substrate.

2. Materials and Methods

The experiment was carried out in a closed room in the laboratory of the Faculty of Forestry at the University of Agriculture in Krakow (50°4′58.442″ N, 19°57′3.922″ E). Two types of Marbet V150 (650/312/150 mm, with 74 cells of 0.145 dm^3 volume) and V300 (650/312/180 mm with 53 cells of 0.275 dm^3 volume) polystyrene containers (Figure 1), commonly used in Poland for the production of coniferous species, e.g., pine, spruce (V150), and deciduous species, e.g., beech and oak (V300), and peat–perlite substrate (95:5 by volume) were used in the experiment [47]. The substrate is produced in Poland at the Nursery Farm in Nędza in the Rudy Raciborskie Forest District based on imported peat, and the percentage of perlite added is determined individually for each batch of peat delivery based on the analysis of air and water capacity. This substrate, based on sphagnum-rich peat, had the following granulometric composition, declared by the producer percentage content of fraction in a unit of volume: 2.5% of 10.1–20 mm fraction, 12.5% of 4.1–10 mm, 12.5% of 2.1–4.0 mm, 72.5% of <2.0 mm; maximum degree of decomposition 15%; organic matter content >5%; and elemental content (g/g of 100% dry weight of the substrate at the beginning of the experiment) of 37.99 ± 0.69 (C), 0.74 ± 0.01 (N), 0.02 ± 0.01 (P).

2.1. Description of the Measuring Station

For the experiment, a leachate table (Figure 2) was designed and constructed that would enable the collection of liquid filtrate and substrate samples from the cells of nursery containers during the long-term irrigation process and fertilization using an irrigation ramp (Figure 1).

Figure 1. V150 (**left**) and V300 (**right**) containers filled with substrate. Photo: M. Kormanek.

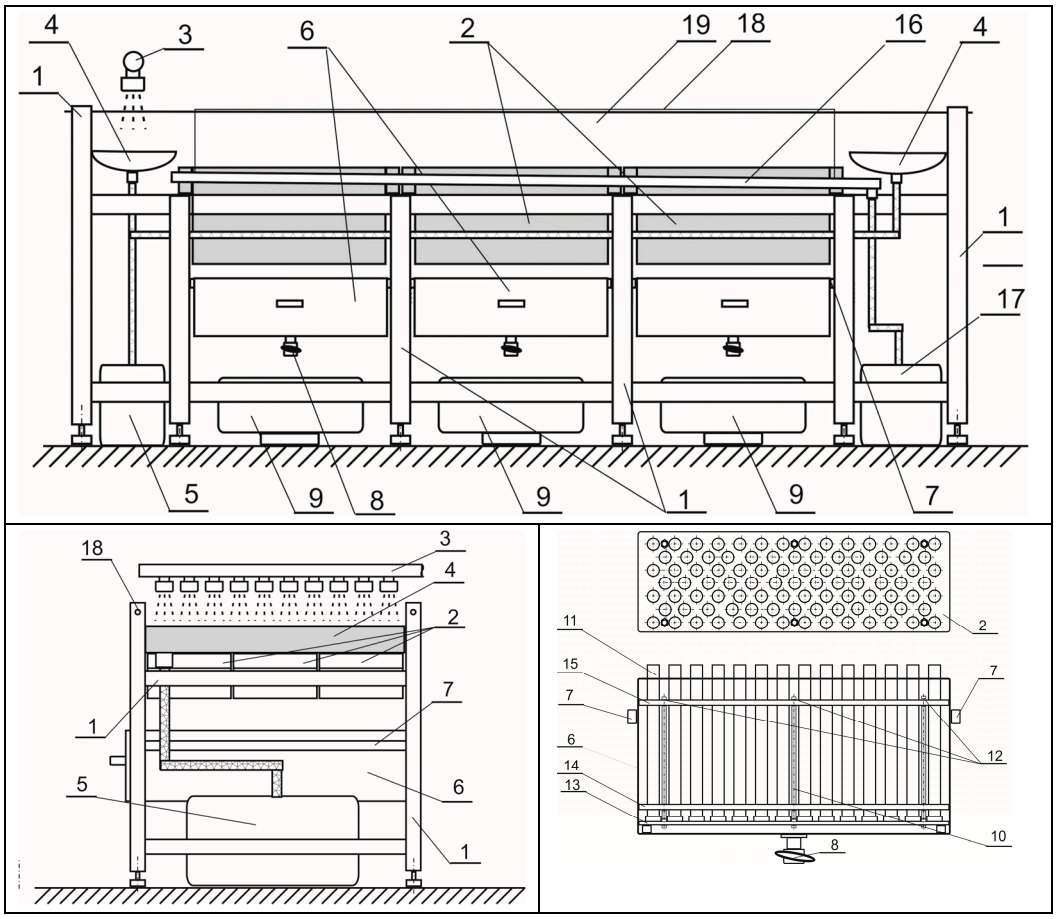

Figure 2. The scheme of a newly developed station for collecting liquid leachate from container cells with a ramp for irrigation and fertilization–Patent 242506 (specified in Section 6): frame (1), containers (2), sprinkler arm (3), drainage gutters I (4), collecting tank I (5), drawers (6), guides (7), valves (8), collecting tanks II (9), drainage racks (10), measuring cylinders (11), rods with nuts (12), base (13), lower templates (14), upper templates (15), drainage gutters II (16), collecting tank II (17), steel cables (18), protective foil (19).

The table consists of a frame (1) on which containers (2) are placed in the upper part. Irrigation and fertilization are carried out by means of a sprinkler arm moving above the table (3). Drainage gutters I(4) are situated at the beginning and end of the frame, in the parts outside the working area that holds the containers, for draining water from under the ramp arm where it sits/starts and turns so that movement along the ramp allows uniform coverage of the containers with the liquid along their entire length. From the gutters, the liquid is drained into a collecting tank (5). Under the containers, there are drawers (6) mounted on guides (7) that can be pulled out completely and reinserted. Each

drawer comprises a rectangular trough, open at the top. Inside each drawer are vertical partitions, dividing it into individual chambers. The external dimensions of each chamber correspond to the surface of the container (2). At the bottom of each chamber, there are outlet openings with drainage connectors attached to valves (8). The liquid drains through these into collection tanks II (9). The outflow of liquid from the nursery containers (2) can be determined from the amount of liquid accumulating at a certain time in the marked collecting tank II (9). In order to measure the outflow of the liquid and to collect samples for chemical analysis from individual cells in the container, draining racks (10) and measuring cylinders (11) are inserted into individual chambers in the drawers (6). The drainage racks (10) consist of rods with nuts (12), base (13) on which the measuring cylinders (11) are placed. The placement of the cylinders was determined by the lower (14) and upper (15) templates, in which holes were made that corresponded to the spacing of the holes in the bottom of the nursery container (2). Thanks to the use of the lower (14) and upper (15) templates, the cylinders (11) could be stabilized in a vertical position. Around the experimental field, with the containers arranged in the upper part of the station, a system of drainage gutters II with a slight slope (16) was installed, through which water that overshoots the nursery containers during sprinkling could drain. These gutters discharge the liquid into a marked collecting tank III (17) to measure the amount of liquid that drained but did not reach the containers. Steel cables (18) are mounted in the upper part on the extreme, higher vertical elements of the frame, on which aprons made of protective foil (19) were mounted so that the working liquid during rain would not splash outside the measuring station and accumulate in longitudinal gutters (16). Based on the amount of water accumulating in the outflow collecting tanks I, II, III (5, 9, and 17) and in the liquid-measuring cylinders (11), a water flow balance could be determined at the drainage station.

The leachate tables were installed in a laboratory prepared for this purpose, where a ramp for irrigation and fertilization, a supply and exhaust ventilation system, a heating system, and a lighting system were also installed (Figure 3).

Irrigation and fertilization were carried out using a modified self-propelled internal sprinkler ramp manufactured by AGRO-SUR Sp. z o.o. The sprinkler arm was shortened to the width of the ramp, which corresponded to the width of the leaching table, and the rail mounted below the ceiling of the laboratory room was the length of the leaching table, plus a section enabling parking and turning of the trolley. The ramp was equipped with a programmable logic controller that allowed the ramp's work cycles to be programmed, along with the length of the ramp's passage, with the possibility of dividing the work area above the tables into sectors for individual irrigation and fertilization. Dosatron fertilizer dosing devices were mounted on the ramp. The ramp was supplied with water from a Grundfos Scala 2 pump with a filtering system and a 600 L tank, to which water from the nursery was delivered from a 1 m^3 tank so that the parameters of the irrigation water would correspond to the parameters of the water used in the nursery. Artificial lighting was not used during the experiment.

2.2. Description of the Tests and Measurements

For the experiment, containers containing substrate (three pieces of V150 and three of V300) were placed randomly on the leachate tables in a randomized block system. The substrate was moistened to 70% volumetric moisture and then vibrated using a vibrating table with an acceleration of 12 $m \cdot s^{-2}$ for a time corresponding to the capacity of the production line of 400 containers per h. The time the container stays on the vibrating table with this line capacity is 12 s. As soon as the containers were filled, they were placed on the leachate tables, and the experiment began, the cycle of which lasted 6 weeks (42 days). On four dates during this time—that is, after the first intensive irrigation, which took place immediately after the containers were placed on the table (T0) and every 14 days thereafter (T1–T3)—the substrates were collected from the cells of the containers and the liquid drained from the cylinders in the drip drawers and directly from the sprinkler ramp. One

dose of irrigation (0.24 $dm^3 \cdot m^2$) was applied three times per day (9:00 a.m., 3:00 p.m., and 9:00 p.m.), and 0,3% (600 $\mu S \cdot cm^{-1}$) doses of fertilizer were applied every 7 days (Floralesad fertilizer, composition in g L^{-1} = 110 N, 21 P, 44 K, 0.5 Ca, 3.4 Mg). The amount of water and fertilizer given during the 42 days of the experiment corresponded to the amount given during the growing season of seedlings in the nursery, which was determined on the basis of measurements made in the year preceding the experiment. The aim was to shorten the duration of the experiment (42 days instead of approximately 210 days of the breeding season in the nursery). The irrigation water from the nursery had a pH of 7.24, conductance of 212 $\mu S \cdot cm^{-1}$, and an elemental content (mg L^{-1}) of 21.73 C, 3.78 N, 0.07 P. The fertilizer concentration during fertilization was controlled each time using an Elmetron CX-705 conductivity meter so that the conductance value was always 600 $\mu S \cdot cm^{-1}$.

Figure 3. Laboratory of irrigation and fertilization techniques for container nurseries with mounted leachate tables.

The physical parameters of the substrate on each measurement date were determined from five cells from each container, starting with the determination of the volume of the

cell filled by the substrate. The level of the substrate was measured from the top surface of the container using a ruler with an accuracy of ±1 mm. From knowing the measurements of the upper surface of the cell opening and the upper level of the substrate, the volume not filled with substrate *Ve* (cm^3) was determined. By subtracting the obtained value *Ve* from the total volume of the cell *V* (cm^3) (V150 = 145 cm^3, V300 = 275 cm^3), the volume occupied by the substrate *Vs* was calculated (in cm^3). Then, a container was placed under the cell from which the substrate was collected, and the water that had dripped out along with the substrate that had flowed out of the cell were collected. The substrate was removed from the top using a plastic spoon, and the material that could not be spooned out was pushed into the tank under the cell. Then, the samples collected from the cell and the tank under the cell were weighed to obtain the wet substrate weight *mw* (in g). The removed substrate was dried to obtain the substrate dry mass *ms* (in g). The dry bulk density *BD* (g cm^{-3}) (1) and the wet bulk density *WBD* (g cm^{-3}) (2) were determined based on this. Also, the substrate for the analysis of the specific bulk density *SPD* (g cm^{-3}) by the boiling method in measuring flasks and the granulometric composition by the sieve method (sieving on air-dry samples) were also taken from the cells [48].

After taking the substrate, the hole was left open so that when they were sealed, the amount of water flowing to the neighboring cells would not increase.

From the specific density *SPD*, the dry bulk density *BD*, and the wet bulk density *WBD*, the overall porosity *OP* (%) (3), water capacity *WC* (%) (4), and air capacity *AC* (%) (5), could be determined.

$$BD = \frac{ms}{Vs} \quad (1)$$

$$WBD = \frac{mw}{Vs} \quad (2)$$

$$OP = \frac{SPD - BD}{SPD} \cdot 100\% \quad (3)$$

$$WC = \frac{mw - ms}{Vs} \cdot 100\% \quad (4)$$

$$AC = OP - WC \cdot 100\% \quad (5)$$

To determine changes in the granulometric composition, the average statistical diameters of the particles *Dp*, defined by Equations (6) and (7), were used [49]:

$$Dp = \frac{\sum_{i=1}^{n} D_i \cdot P_i}{100\%} \quad (6)$$

where *Dp* = mean statistical particle diameter (mm); P_i = percentage content of the *i* th fraction (%); *n* = number of fractions; and D_i = mean particle diameter of the *i* th fraction (mm).

D_i—mean particle diameter of the *i*-th fraction (mm)

$$D_i = \frac{D_{imax} + D_{imin}}{2} \quad (7)$$

where D_{imax} = maximum diameter of the *i* th fraction (mm); and D_{imin} = minimum diameter of the *i* th fraction (mm).

2.3. Chemical Analysis

At each time point (T0–T3), the collected substrate samples were dried at 65 °C for 48 h and then ground to powder, and their chemical properties were determined following Ostrowska et al. [50]. The C and N content was determined using a LECO CNS True Mac Analyzer (Leco, St. Joseph, MI, USA). The samples were then analyzed by inductively coupled plasma optical emission spectroscopy (ICP–OES ThermoiCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK). The results were converted into the dry weight of the

substrate. The analysis took into account the average volume in the form of dry mass from the obtained substrate after each measurement series. Therefore, we decided to convert the obtained values into g of dry mass per container. The liquid filtrate samples from the drip tables and the samples of working liquid from the ramp were analyzed for pH, measured using the potentiometric method, and their electrolytic conductivity using an Elmetron CX-705 multifunctional device, and the amount of liquid filtered from the substrate was determined (in mL). Then, the liquid was filtered through a Munktel 390 hard filter, and the samples were analyzed by ICP–OES to determine the P content.

2.4. Statistical Analysis

A two-way analysis of variance of the differences in the values of the physical parameters and elemental contents was performed for both types of containers (V150, V300) and each sampling date (T0–T3). First, it was checked whether there were differences in parameters due to the type of container (V150, V300) for the entire measurement time, then due to the sampling date (T0–T3) for a given type of container (V150, V300), and then interactions of the type of container (V150, V300) and sampling date (T0–T3). Spearman correlation coefficients between individual chemical parameters and physical properties were calculated. Tukey's honestly significant difference test was used to evaluate the differences between the mean values of the characteristics. The results were considered statistically significant at $\alpha < 0.05$. All statistical analyses were performed using R 4.1.3 statistical software, R Studio [51], and Statistica 13 [52].

3. Results

3.1. Physical Parameters

The specific density, wet bulk density, dry bulk density, total porosity, and air and water capacity were different between the V150 and V300 containers (Table 1).

Table 1. The physical parameters of the substrate in containers V150 and V300 for the entire measurement time.

Container Type	*SPD* g·cm^{-3}	*WBD* g·cm^{-3}	*BD* g·cm^{-3}	*OP* %	*WC* %	*AC* %
V150	1.477 ± 0.141 ^{a}	0.562 ± 0.176 ^{b}	0.099 ± 0.01 ^{a}	93.24 ± 0.93 ^{b}	41.81 ± 5.20 ^{b}	51.43 ± 4.88 ^{a}
V300	1.327 ± 0.124 ^{b}	0.843 ± 0.090 ^{a}	0.180 ± 0.02 ^{b}	86.31 ± 1.64 ^{a}	33.13 ± 6.02 ^{a}	53.19 ± 6.34 ^{a}
	F = 41.5 p = 0.000 **	F = 211.2 p = 0.000 **	F = 1379.6 p = 0.000 **	F = 811.8 p = 0.000 **	F = 71.5 p = 0.000 **	F = 2.9 p = 0.090
Average for V150 and V300 containers	1.399 ± 0.118	0.702 ± 0.119	0.139 ± 0.04	89.78 ± 3.72	37.47 ± 7.10	52.31 ± 5.70

Designations: *SPD* specific bulk density, *WBD* wet bulk density (g·cm^{-3}), *BD* dry bulk density (g·cm^{-3}), *OP* overall porosity (% vol.), *WC* water capacity (% vol.), and *AC* air capacity (% vol.). For F-test: degrees of freedom 1, treatment 120, residual 118, and total 119. Significant differences were marked "**" at <0.01, ^{ab} the same letter denote homogeneous groups; Tukey HSD $p < 0.05$.

Irrigation and fertilization of the substrate over the long term caused a change in the physical parameters of the substrate in the container cells (Table 2). In both the V150 and V300 containers, the specific density, wet bulk density, and water capacity increased, while the dry bulk density and air capacity decreased. The substrate settled over time, and with periodic irrigation, the fine particles inside the cells moved. Both differences in the volume of cells in containers and the date of sampling influenced all analyzed parameters.

Table 2. Substrate physical parameters in containers and terms; T0–T3—terms of collecting samples.

Container	Term	*SPD* g·cm^{-3}	*WBD* g·cm^{-3}	*BD* g·cm^{-3}	*OP* %	*WC* %	*AC* %
V150	T0	1.33 ± 0.032 ^{au}	0.536 ± 0.100 ^{au}	0.100 ± 0.006 ^{bcyz}	92.5 ± 0.43 ^{au}	36.12 ± 4.44 ^{au}	56.38 ± 4.78 ^{dy}
	T1	1.47 ± 0.023 ^{cx}	0.565 ± 0.095 ^{au}	0.106 ± 0.005 ^{cz}	92.8 ± 0.34 ^{au}	40.70 ± 3.35 ^{bz}	52.13 ± 3.56 ^{cx}
	T2	1.41 ± 0.014 ^{bw}	0.573 ± 0.074 ^{au}	0.097 ± 0.011 ^{abxy}	93.1 ± 0.80 ^{au}	43.93 ± 2.89 ^{cw}	49.18 ± 3.07 ^{buw}
	T3	1.67 ± 0.01 ^{dz}	0.573 ± 0.057 ^{au}	0.092 ± 0.008 ^{ax}	94.5 ± 0.46 ^{az}	46.50 ± 3.24 ^{cw}	48.01 ± 3.28 ^{auw}
F-test (Term)		F = 421.27 p = 0.000 **	F = 5.57 p = 0.064	F = 8.42 p = 0.000 **	F = 4.02 p = 0.753	F = 2.41 p = 0.000 **	F = 1.49 p = 0.000 **
V300	T0	1.33 ± 0.23 ^{au}	0.719 ± 0.114 ^{ax}	0.182 ± 0.007 ^{auw}	86.38 ± 0.56 ^{aw}	26.85 ± 5.58 ^{ax}	59.53 ± 5.79 ^{dz}
	T1	1.38 ± 0.26 ^{bx}	0.800 ± 0.099 ^{by}	0.185 ± 0.007 ^{aw}	86.54 ± 0.74 ^{bw}	30.78 ± 4.84 ^{by}	55.76 ± 4.71 ^{cy}
	T2	1.45 ± 0.15 ^{cx}	0.917 ± 0.051 ^{cw}	0.179 ± 0.010 ^{auw}	87.70 ± 0.66 ^{cy}	36.92 ± 2.38 ^{cu}	50.77 ± 2.62 ^{bwx}
	T3	1.41 ± 0.14 ^{dw}	0.935 ± 0.037 ^{cw}	0.176 ± 0.025 ^{au}	86.63 ± 2.20 ^{bx}	37.95 ± 2.04 ^{cu}	46.68 ± 2.22 ^{au}
F-test (Term)		F = 314.89 p = 0.000 **	F = 23.23 p = 0.000 **	F = 1.08 p = 0.366	F = 15.62 p = 0.000 **	F = 25.68 p = 0.000 **	F = 28.16 p = 0.000 **
F-test (Container × term)		F = 54.21 p = 0.000 **	F = 217.04 p = 0.000 **	F = 768.2 p = 0.000**	F = 241.91 p = 0.000 **	F = 44.1 p = 0.000 **	F = 19.89 p = 0.000 **

Designations: *SPD* specific bulk density, *WBD* wet bulk density (g cm^{-3}), *BD* dry bulk density (g cm^{-3}), *OP* overall porosity (% vol.), *WC* water capacity (% vol.), and *AC* air capacity (% vol.). For the F-test, due to the term: degrees of freedom 1, treatment 3, residual 56, and total 59. For the F-test, container type × term: degrees of freedom container-1 term-3, treatment 3, residual 112, and total 119. Significant differences were marked "**" < 0.01. ^{abcd} denotes homogeneous groups within the term, ^{uwxyz} denotes homogeneous groups within the container × term; Tukey HSD $p < 0.05$

The granulometric composition of the substrate immediately after filling the containers was dominated by the 1–5-mm fraction, assuming 32.67%–32.88% for the V150 containers and 22.62%–23.21% for the V300 (Figure 4). Over time, the smallest (<0.5 mm) fraction increased in the V150 container, while the share of fractions with larger diameters increased in the V300 container.

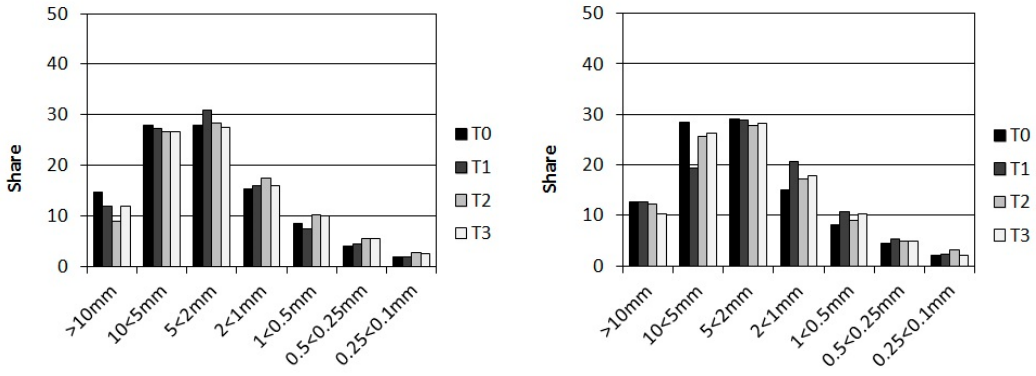

Figure 4. Change in the granulometric composition of the substrate over time in the V150 (**left** figure) and V300 (**right** figure) containers; T0–T3—terms of collecting samples.

This was confirmed by the average particle diameter data (Figure 5), which, after backfilling, was 1.25 mm in the V150 container and 0.82 mm in the V300 container. This parameter indicates that, over time, there was a breakdown of larger substrate particles in

the cells of the V150 containers and an aggregation of fine particles in the V300 containers. The particle size values at the end of the experiment were similar in both containers (V150 = 0.99 mm and V300 = 0.96 mm).

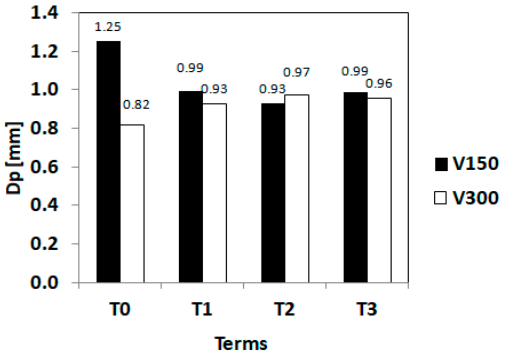

Figure 5. Change over time of the average statistical diameter of the substrate particles; T0–T3—terms of collecting samples.

3.2. Chemical Parameters

The chemical analysis showed statistically significant differences between the type of container and the accumulation of individual elements in the substrate and leachate (Table 3). Only the C content in leachate did not differ statistically between V150 and V300 containers. Higher contents of C, N, and P in the substrate were determined in containers dedicated to deciduous species (V150). However, higher values of the same elements in leachates were determined under containers dedicated to coniferous species (V150).

Table 3. Chemical properties of selected elements (in mg/container) contained in the substrate.

Container Type	C	N	P	C	N	P
		Substrate			Leachate	
V150	5267.5 ± 2055.9 ^{y}	7786.8 ± 833.1 ^{y}	212.7 ± 30.1 ^{y}	1262.5 ± 945.5 ^{x}	236.6 ± 203.2 ^{x}	116.0 ± 106.4 ^{x}
V300	6903.1 ± 2605.2 ^{x}	10,123.8 ± 993.8 ^{x}	273.9 ± 48.9 ^{x}	1083.4 ± 550.3 ^{x}	107.3 ± 47.2 ^{y}	71.8 ± 46.9 ^{y}
	F = 12.71 p = 0.000 **	F = 175.91 p = 0.000 **	F = 63.01 p = 0.000 **	F = 1.81 p = 0.181	F = 21.51 p = 0.000 **	F = 10.42 p = 0.001 **
V150 and V300	6085.2 ± 2476.9	8955.3 ± 1486.8	243.3 ± 50.8	1173.0 ± 775.5	169.7 ± 158.4	93.7 ± 84.6

Mean ± SD; small letters xy—the difference between the volume of the cell, For the F-test: degrees of freedom 1, residual 113, and total 114; Significant differences were marked "**" < 0.01. Tukey HSD $p < 0.05$.

In addition, statistically significant differences were found between the different sampling times (Table 4). Along with the water, fertilizer was applied directly from the sprinkler ramp to the surfaces of the containers at times T0–T3. The lowest values of the elements delivered with irrigation were recorded at T0 before the use of fertilizers. The highest C content in the substrate was found at T0 and decreased over time. The highest N content in the substrate was found in the T1 series; smaller containers (V150) showed lower values compared to larger containers (V300). The lowest P content in the V150 containers was recorded at T0, the values ranging from 180.6 to 241.8 mg per container, while in the V300 containers, the values oscillated between 235.1 and 336.6 mg per container (Table 4).

Table 4. Chemical properties of selected elements (in mg/container) contained in ramp water, substrate, and leachate.

			C	N	P
Ramp water		T0	11.9 ± 1.9 ^{b}	3.6 ± 0.2 ^{b}	0.42 ± 0.1 ^{c}
		T1	78.3 ± 1.9 ^{a}	76.4 ± 1.9 ^{a}	14.5 ± 0.05 ^{b}
		T2	70.3 ± 9.6 ^{a}	85.4 ± 11.3 ^{a}	27.8 ± 3.5 ^{a}
		T3	47.9 ± 19.3 ^{a}	88.0 ± 5.7 ^{a}	19.5 ± 0.9 ^{b}
		F-test	F = 23.68 p = 0.002 **	F = 130.78 p = 0.000 **	F = 129.32 p = 0.000 **
Substrate	V150	T0	6059.9 ± 1257.9 ^{auw}	7887.4 ± 610.1 ^{abwx}	180.6 ± 10.6 ^{cz}
		T1	5208.5 ± 1132.4 ^{auw}	8439.3 ± 587.5 ^{aw}	216.1 ± 25.1 ^{by}
		T2	4113.5 ± 1473.1 ^{aw}	7473.6 ± 860.5 ^{bwx}	212.2 ± 24.1 ^{by}
		T3	5687.9 ± 3238.2 ^{auw}	7346.9 ± 829.21 ^{bx}	241.8 ± 21.9 ^{axy}
		F-test	F = 1.69 p = 0.1693	F = 1.569 p = 0.207	F = 31.99 p = 0.000 **
	V300	T0	7824.3 ± 1910.8 ^{au}	10,066.2 ± 518.3 ^{au}	235.1 ± 12.3 ^{cxy}
		T1	7255.1 ± 2707.5 ^{au}	10,584.4 ± 1129.1 ^{au}	251.4 ± 19.6 ^{bcwx}
		T2	6733.6 ± 3441.3 ^{auw}	9969.64 ± 697.3 ^{au}	272.6 ± 20.5 ^{bw}
		T3	5799.2 ± 1844.0 ^{auw}	9874.9 ± 1345.1 ^{au}	336.6 ± 52.5 ^{au}
		F-test	F = 1.69 p = 0.179	F = 1.57 p = 0.207	F = 31.99 p = 0.000 **
	F-test (Container × term)		F = 1.66 p = 0.180	F = 0.36 p = 0.784	F = 6.55 p = 0.001 **
Leachate	V150	T0	485.9 ± 119.9 ^{bx}	78.4 ± 22.1 ^{cx}	32.9 ± 18.9 ^{cz}
		T1	661.8 ± 344.9 ^{bx}	98.3 ± 61.6 ^{cx}	48.3 ± 14.3 ^{cyz}
		T2	1741.9 ± 666.6 ^{aw}	272.6 ± 94.8 ^{bw}	163.7 ± 78.3 ^{bw}
		T3	2160.4 ± 1023.2 ^{au}	495.6 ± 201.2 ^{au}	234.3 ± 118.7 ^{au}
		F-test	F = 28.76 p = 0.000 **	F = 42.02 p = 0.000 **	F = 30.21 p = 0.000 **
	V300	T0	565.9 ± 196.1 ^{bx}	68.1 ± 17.2 ^{bx}	32.2 ± 15.5 ^{cz}
		T1	746.1 ± 313.65 ^{bx}	78.3 ± 16.9 ^{bx}	35.4 ± 14.5 ^{cz}
		T2	1628.4 ± 408.7 ^{aw}	135.8 ± 34.5 ^{ax}	123.8 ± 40.4 ^{awx}
		T3	1393.2 ± 377.2 ^{aw}	147.1 ± 49.9 ^{ax}	95.9 ± 23.5 ^{bxy}
		F-test	F = 34.72 p = 0.000 **	F = 22.38 p = 0.000 **	F = 46.89 p = 0.000 **
	F-test (Container × term)		F = 7.06 p = 0.000 **	F = 27.81 p = 0.000 **	F = 13.16 p = 0.000 **

Mean ± SD; comparison of the T0-T3 sampling series; small letters ^{abc} denotes homogeneous groups within the term, ^{uwxyz} denotes homogeneous groups within the container x term. For the F-test, due to the term: degrees of freedom 1, treatment 3, residual 51, and total 54. For the F-test, container type × term: degrees of freedom container-1 term-3, treatment 3, residual 107, and total 114; Significant differences were marked "**" < 0.01. Tukey HSD $p < 0.05$

The amount of elements leached from the cassettes increases with the collection time. In the V150 containers, the values ranged from 485.9 to 2169.4 for C, from 78.4 to 495.6 for N, and from 32.9 to 234.3 mg for P. In this variant, statistically significant differences were recorded between the date of collection. Similar relationships were found for V300 containers, except for the T2, where higher C and P values were recorded in T3. C values

ranged from 565.9 to 1628.4, N content ranged from 68.1 to 147.1 mg, and P values ranged from 32.2 to 123.8 (Table 4).

A strong positive correlation was found only between element contents in leachate. No correlation was found between the content of individual elements in leachates and the values of the physical parameters of the substrate (Figure 6).

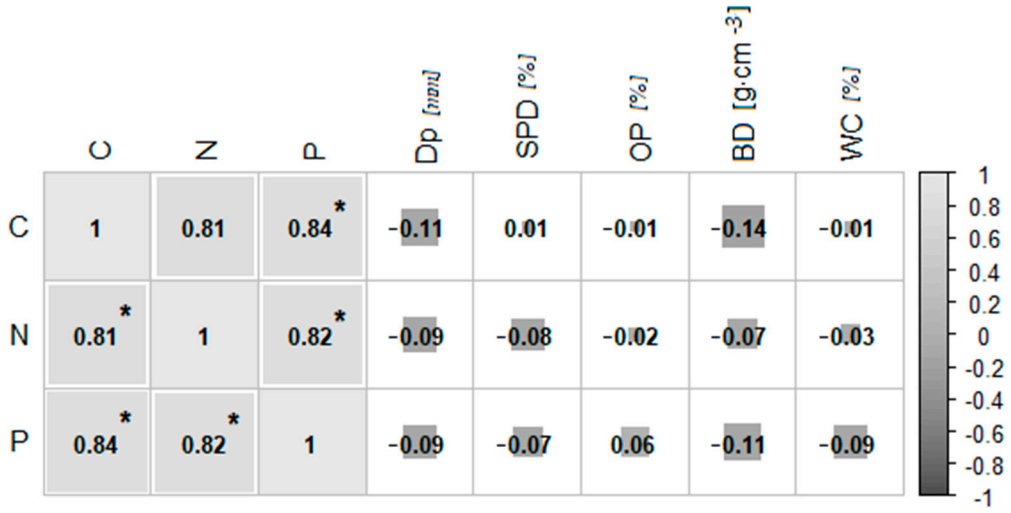

Figure 6. The relationship between elemental content of leachate and physical properties; Dp-average particle diameter; SDP-solid phase density; OP-overall porosity; BD-bulk density; and WC-water capacity, Significance effect * $\leq$ 0.05.

4. Discussion

Despite the wide use of peat as the basic component in substrates for plant production [45], there has been relatively little research on this material [46]. With the availability of this material rapidly changing [44] and an alternative needing to be found, optimizing its consumption and determining its characteristics are important. Our novel experimental setup and analyses confirmed the utility of the leachate tables for determining the physical and chemical parameters of the substrate and its pattern of accumulation of elements. The leachate table was found to be a suitable tool for introducing precise doses of water and fertilizer to the substrates, as well as for monitoring the leaching rate of dissolved elements under controlled conditions.

From the results, we found that, despite applying identical methodology to filling the containers with the same substrate, there were differences in the basic physical parameters in the containers with different cell volumes. Higher specific density *SPD* and dry bulk density *BD* values in the V300 container were associated with the larger cell volume (V300 = 275 cm^3, V150 = 145 cm^3) and the process of compacting the substrate on the vibrating table (Figure 3). The greater share of large fractions in the substrates of the cells with a smaller volume and smaller inlet opening indicated weaker vibration and the migration of the large fractions into the center of the cell. Both the wet bulk density *WBD* and the water capacity *WC* were higher in the cells with a smaller diameter (V150), indicating better water retention in larger soil spaces. This highlights the need for individual adjustments to be made to the vibration of the vibrating table in relation to the size of the cell in the container. The change in the mean diameter of the substrate particles *Dp* was interesting, indicating a change in the composition of the granulometric fraction with time, irrigation, and fertilization, as well as its unification of the substrate fraction in both types of containers (Figure 4).

The water reaching the substrate directly with the fertilizer delivered more of the elements to the substrate, but these accumulated less in the substrate due to greater leaching (Figure 6 and Table 4). A similar relationship was previously observed by Yang et al. [53], who found an increase in the content of leached elements in the leachates caused by an

increase in the concentration of fertilizer delivered. Our results show a systematic leaching of C and N from the substrate, whereas the P content at T3 increased significantly. This is probably due to the substrate being able to easily bind to P, allowing less leaching [54]. There is also evidence that, under natural conditions and after a certain period of time, the substrate can stabilize, leading to a lessened likelihood of nutrient loss [55].

5. Conclusions

The novel leachate table made it possible to determine changes in the physical and chemical parameters of the substrates in the container cells resulting from long-term irrigation and fertilization. Filling the nursery containers with the substrate under the same vibration and initial moisture conditions resulted in the cells containing different fractions of the substrate caused by the different cell volumes. In the cells with smaller volumes, the larger-diameter fraction was dominant, whereas there was a greater share of the smaller-diameter fraction in the larger cells. This could have been responsible for the differences in the substrate air and water capacity between the different sizes of containers, thus highlighting the need to select individual vibration parameters for each type of container. Over time, there was a change in the granulometric composition of the substrate in the containers, with the mean-size shares of the substrate particles becoming similar in the containers with cells of different volumes. Lower accumulation of elements in the substrate with an increase in the amount of elements applied through fertilization, followed by their greater leaching and higher content in the leachates.

This study confirmed that filling parameters on the automated lines should be selected individually for specific container types.

The use of new drainage tables shortens the time of testing potential substrates for nursery production and allows the rejection of those whose parameters differ significantly from the assumed ones, even before the experiment with seedlings (requiring a longer time).

6. Patents

Patent 242506. Station for collecting liquid filtrate samples from nursery containers. Kormanek M.; Małek, S.; Banach, J.; and Mateusiak Ł. Application to the Polish patent office on 2021-09-10.

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