INFLUENCE OF SUBSTRATE TYPE ON SEED GERMINATION AND EARLY PLANT DEVELOPMENT UNDER CONTROLLED CONDITIONS
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INFLUENȚA TIPULUI DE SUBSTRAT ASUPRA GERMINĂRII SEMINȚELOR ȘI DEZVOLTĂRII TIMPURII A PLANTELOR ÎN CONDIȚII CONTROLATE

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ABSTRACT
The study investigates the influence of different substrates on seed germination and early plant development under controlled environmental conditions, using a specially designed intelligent plant growth simulation system. Experiments were conducted with lettuce and radish seeds sown in peat, garden compost, and podzol. The system allowed precise control of temperature, humidity, soil moisture, light, and carbon dioxide, enabling a reliable comparison of treatments. The initial physical and chemical properties of the substrates were characterized, showing the lowest moisture and density in peat, while compost and podzol displayed higher values and more balanced nutrient content. The results demonstrated that lettuce germinated successfully across all substrates, although peat delayed germination by 5–7 hours and true leaves appearance by up to 12 hours. In radish, the effect was more pronounced: compost and podzol ensured rapid germination (94–95 hours) with high success rates (~98%), whereas peat resulted in delays exceeding 100 hours and germination rates below 25%. Correlation analyses highlighted strong links between delayed germination and reduced performance, especially in peat. Overall, the study confirmed that substrate choice is critical for achieving uniform and efficient germination, with compost and podzol providing optimal conditions, and emphasized the practical value of simulation systems for improving crop establishment.

REZUMAT
Studiul urmărește influența diferitelor substraturi asupra germinării semințelor și dezvoltării timpurii a plantelor în condiții controlate, utilizând un sistem inteligent de simulare a creșterii plantelor. Experimentele au fost realizate cu semințe de salată și ridiche semănate în turbă, compost de grădină și sol de tip podzol. Sistemul a permis controlul precis al temperaturii, umidității, umidității solului, luminii și dioxidului de carbon, asigurând o comparație fiabilă între variante. Proprietățile fizico-chimice inițiale ale substraturilor au fost determinate, rezultatele evidențiind cele mai scăzute valori de umiditate și densitate pentru turbă, în timp ce compostul și podzolul au prezentat niveluri mai ridicate și un conținut nutritiv mai echilibrat. Rezultatele au arătat că salata a germinat cu succes pe toate substraturile, deși turba a întârziat germinarea cu 5–7 ore și apariția frunzelor cu până la 12 ore. În cazul semințelor de ridiche, efectul a fost mai pronunțat: compostul și podzolul au asigurat o germinare rapidă (94–95 ore) cu rate de succes ridicate (~98%), în timp ce turba a determinat întârzieri de peste 100 ore și rate de germinare sub 25%. Analizele de corelație au evidențiat legături puternice între întârzierile de germinare și reducerea performanței, mai ales pentru turbă. În ansamblu, studiul a confirmat că alegerea substratului este esențială pentru obținerea unei germinări uniforme și eficiente, compostul și podzolul oferind condiții optime, și a subliniat valoarea practică a sistemelor de simulare pentru îmbunătățirea instalării culturilor.

INTRODUCTION
As the global population continues to grow, the provision of food with equal accessibility has become a major issue and a future challenge. To meet both the worldwide demand for food security and the new environmental requirements, agriculture must increase food production and quality while simultaneously reducing its negative impact on ecosystems and the environment. (*Belanger and Pilling, 2019; FAO, 2023*).

Soil moisture has decreased significantly in the southern region and increased in parts of northern Europe since the 1950s. Similar effects are expected in the coming decades, as average temperatures continue to rise and precipitation patterns change. Climate change is affecting rainfall, water flows, soil moisture, and temperature. The frequency and magnitude of extreme weather and climate events will increase, and the distribution and abundance of pests and pollinators may shift. These changes will influence crop growth, phenology, and yields, ultimately leading to drastic changes in the areas suitable for cultivating specific plants and changes in land use (*Orkic et al., 2025*).

Plant development and crop productivity are strongly influenced by multiple environmental and management factors, including water availability at different growth stages, light intensity and duration, substrate, nutrient supply, temperature, and humidity. At the same time, global agriculture is increasingly challenged by rapid population growth—particularly in urban areas—and by the progressive depletion of natural resources. As environmental pressures intensify, the COVID-19 pandemic has also exposed the vulnerability of global food systems. One of the most pressing challenges for the coming decades is therefore to ensure adequate nutrition for expanding urban populations, while simultaneously addressing the social, economic, and environmental demands associated with sustainable urban development (*Chini et al., 2024; Dumitrescu et al., 2022; Kosakova et al., 2025; Li et al., 2024; Timlin et al., 2023*).

In this context, plant cultivation under controlled conditions-such as greenhouses, vertical farms, and growth chambers - offers a sustainable alternative, enabling year-round production, efficient resource use, and reduced vulnerability to climatic fluctuations. These systems not only address the challenge of feeding growing cities but also provide opportunities for integrating agriculture into urban environments, thereby reducing supply chain vulnerabilities (*Arcas-Pilz et al., 2022; Glaros et al., 2024; Van Gerrewey et al., 2022; Vatistas et al., 2022*).

Seed germination represents the first and most critical phase in the plant life cycle, as it determines both the establishment and the potential productivity of crops. Successful germination ensures uniform crop stands, stronger seedlings, and optimal resource use throughout the growing season. Conversely, poor or delayed germination can result in reduced plant density, uneven growth, and lower yields, with direct consequences for food security and agricultural efficiency. As germination is highly sensitive to environmental factors such as water availability, temperature, light, and substrate properties, its optimization is essential for improving crop performance under both conventional and controlled cultivation systems (*Barbosa et al., 2015; ISTA Germination Committee, 2006; Jama-Rodzeńska et al., 2021; Kanjevac et al., 2022; Neofytou et al., 2024; Pirredda et al., 2023; Rahmadi et al., 2024*).

Soil physical properties influence seed germination, as they modulate oxygen diffusion, water retention, and mechanical resistance at the seed–soil interface, thereby altering germination success (*Bernal et al., 2019; Logachev and Goncharov, 2024*). In fine-textured clay soils, higher mechanical impedance and lower macroporosity restrict gas exchange and hinder emergence—effects that are especially pronounced for small-seeded species (*Benvenuti and Mazzoncini, 2023; Kollárová et al., 2025*). Soil oxygen availability, often reduced by compaction or waterlogging, also limits germination: under controlled O_2 gradients, several weed species showed significantly lower germination already at 15% O_2, and only the most tolerant taxa maintained ~34–58% germination at 2.5% O_2 (*Yasin and Andreasen, 2019*). Substrate composition has a great impact as well: mixing vermicompost / semi-compost with peat improved lettuce germination to 94.5 ± 1.9, illustrating the benefits of organic amendments for aeration and nutrient supply (*Hernández-Rodríguez et al., 2017*). Soil pH exerts species-specific constraints; for example, common ragweed exhibited germination ratios ≥~50% across pH 5–7, with poorer performance at more extreme pH values (*Gentili et al., 2018*).

The paper presents experimental research for determining the effect of substrate on the germination of seeds and their early development in controlled growth conditions.

MATERIALS AND METHODS

To determine the effect of soils on the germination of seeds, experiments were conducted, sowing two types of crop seeds (lettuce and radish – Figure 1) on three types of soils (garden compost, peat and podsol – Figure 2) and following the germination process until the development of the firsts two true leaves.

The three substrates were selected to represent contrasting physical and chemical conditions influencing seed germination. *Garden compost* is an organic-rich, mature substrate with high microbial activity and balanced nutrient content, providing favourable aeration and moisture retention. *Peat* was chosen due to its widespread use in horticulture, characterized by low bulk density, high porosity, and acidic pH, but low mineral nutrient content. *Podsol* represents a naturally occurring mineral soil with higher density and moderate organic matter, offering intermediate aeration and water-holding capacity.

Fig. 1 - Seeds used for experiments

Garden compost Peat Podsol

Fig. 2 - Soil substrates used for experiments

Lettuce (*Lactuca sativa L.*) and radish (*Raphanus sativus L.*) were chosen because they differ in seed size, dormancy, and water/nutrient sensitivity, making them suitable indicators of substrate influence. Lettuce has small, light-sensitive seeds commonly used in germination studies, whereas radish has larger seeds that reveal differences in oxygen diffusion and moisture dynamics across substrates.

The experiments were conducted using a specially designed equipment (presented in Figure 3) that enables the simulation of various environmental parameters.

Fig. 3 - System for the simulation of plant growth conditions

The system consists of the following main components: a support frame; wheels for easy movement; a lighting system for simulating plant germination and growth under various light periods and intensities; an irrigation/fertigation system; a shoot chamber for studying and monitoring the above-ground parts of the plants; a root system chamber for observing and monitoring root development, consisting of transparent containers open at the top to allow the plant to grow into the shoot chamber and with small openings at the bottom; a collection chamber for excess water and nutrients, which collects water and any unused fertilizers, pesticides, or herbicides (FPHs) that are washed from the soil into the collection tray; and a control and monitoring system.

The three compartments—separate growth chambers have the following characteristics: the aerial parts chamber for the above-ground parts of the plants (1.49 m^3 in volume), the root chamber where plant roots develop (with 6 vessels each 0.17 m^3 in volume), and the collection chamber where excess irrigation water is collected to evaluate water retention in the substrate under various conditions (0.03 m^3 in volume). It includes a lighting system capable of simulating light (6,500-55,000 lux), which enables the simulation of the photosynthesis process for the plant; a plant watering (irrigation) system divided into two parts—drip irrigation at the plant level and overhead watering that simulates rainfall (1000 l/h max flowrate); a heating assembly equipped with a temperature sensor (range 0-60 ºC, accuracy ±0.2 ºC); a ventilation assembly (940 m^3/h yield) with humidity sensors; a CO_2 enrichment unit with a CO_2 sensor (0-10000 ppm range); and a control box equipped with a Programmable Logic Controller (PLC) for monitoring and controlling the plant growth simulation program. The system also features a time-lapse camera for continuous monitoring and evaluation of germination and plant development.

For the experimentation of seed germination in controlled conditions, the following methodology was used:
- the seeds were prepared for sowing (calculation were made for the mass of 1000 seeds, seed moisture);
- the substrate was prepared for sowing (the initial moisture and density of the substrate were determined using the oven, the thermobalance, and by calculation with a container of known volume filled with substrate);
- the seeds were sown (100 seeds for lettuce and 12 seeds for radish);
- the soil was preliminary watered with a predetermined amount of water (500 ml for each growth container);
- the parameter control program (Figure 4) was set via the PLC in the automation box.

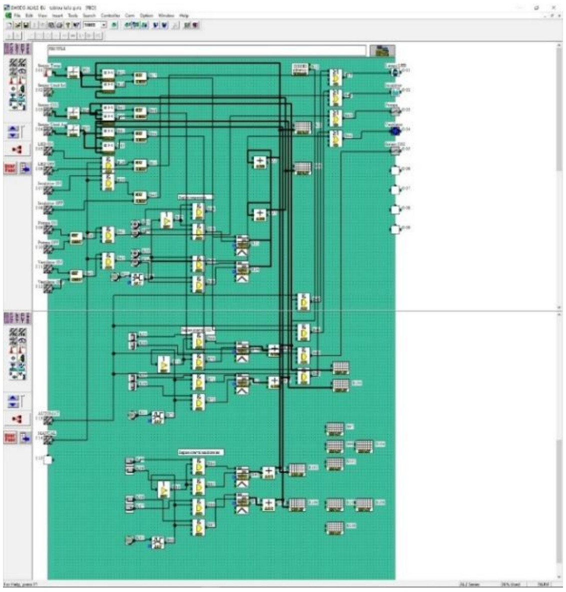

Fig. 4 - Plant growth simulation program created in AL-PCS/WIN-EU

Using AL-PCS/WIN-EU, the program for plant growth was created as follows: the lighting duration for the plants after emergence was set to 10 hours per day using a colour combination of 4000K white and 660 nm red, to provide both broad-spectrum illumination and efficient photosynthetic stimulation. During the experiments, the substrates were irrigated through pre-determined soil-level watering as to maintain a soil moisture adequate for germination and immediate growth. The temperature was set at 20 °C, soil moisture at 60%, air humidity at 65%, and CO_2 level at 400 ppm.

The initial moisture of the substrate used was determined by drying soil in the laboratory oven (Memmert-UFE 500) at 105 ^oC for 16 hours, and the results are presented in Table 1.

Table 1

Initial moisture of the substrate used

Sample	Substrate	Moisture [%]
1	Podsol	32.44
2	Peat	16.70
3	Garden Compost	28.78
4	Podsol	30.89
5	Peat	16.45
6	Garden Compost	28.94
7	Podsol	31.93
8	Peat	16.60
9	Garden Compost	29.08

Although soil moisture was maintained at 60% during the experiments, the initial moisture content of each substrate can determine its water absorption rate and equilibrium time under the controlled irrigation regime. Substrates with very low initial moisture (such as peat) required more time to reach uniform hydration, especially on a large soil horizon, delaying the establishment of optimal germination conditions during the first hours after sowing. Therefore, initial moisture served as an indicator of substrate hydrophilicity and affected early water availability to the seeds, which is critical for the imbibition phase preceding germination.

The initial density of the substrate used was determined using a known volume cylindrical contained and then weighing the samples. The results from determinations are presented in Table 2.

Table 2

Initial density of the substrate used

Sample	Substrate	Density [kg / m^3]
1	Podsol	532
2	Peat	214
3	Garden Compost	383
4	Podsol	517
5	Peat	205
6	Garden Compost	361
7	Podsol	534
8	Peat	202
9	Garden Compost	391

The main nutrients content (N, P, K) was determined using a Biobase BK-Y6A equipment, the results from determinations being presented in Table 3.

Table 3

Main nutrients content of the substrate used

Sample	Substrate	N content [g/l]	P content [g/l]	K content [g/l]	PH
1	Podsol	0.94	1.58	1.62	5.8
2	Peat	0.21	0.24	0.37	5.6
3	Garden Compost	0.90	1.32	1.24	5.6
4	Podsol	0.88	1.64	1.59	5.8
5	Peat	0.22	0.23	0.38	5.8
6	Garden Compost	0.88	1.30	1.25	5.8
7	Podsol	0.95	1.65	1.67	5.9
8	Peat	0.22	0.24	0.38	5.6
9	Garden Compost	0.90	1.30	1.22	5.6

The initial physical properties of the substrates indicated the lowest moisture and density for peat (average values of 16.6% and 202 kg/m^3), while podzol and garden compost showed higher and closer values (average 31–32% moisture and 361-534 kg/m^3 density). These parameters directly influenced the germination dynamics.

During the experiments, the main stages of seed germination and early plant development were monitored, namely the germination time, the appearance of the first pair of true leaves, and the germination rate depending on the type of substrate used.

RESULTS

The experimental tests carried out using the intelligent plant growth simulation system revealed consistent and significant differences between the three substrates analysed (peat, garden compost, and podzol).

For lettuce seeds, germination time ranged between 45 and 53 hours, with the shortest times recorded in podzol and compost, while peat consistently caused delays of 5–7 hours compared to the other substrates. For radish seeds, germination occurred between 94 and 101 hours, again with podzol and compost providing the fastest response, whereas peat extended the process by several hours.

The emergence of the first true leaves followed a similar pattern. For lettuce, leaves appeared after 62–76 hours, while for radish the interval was 72–82 hours. In both species, the longest delays were consistently associated with peat-based pots, confirming the substrate's weaker performance.

The germination rate for lettuce was generally high across all substrates (89–98%), with only slight reductions in peat.

In contrast, radish seeds showed a clear substrate-dependent response: maximum germination (91–100%) was achieved in podzol and compost, but peat displayed extremely low and unstable values (16–25%). This highlights the negative influence of peat's low water retention capacity on radish germination success.

Figures 5–7 illustrate the comparative evolution of germination time, leaf appearance, and germination percentage across the analysed substrates and plant species, while also emphasizing the greater variability and lower stability observed in peat.

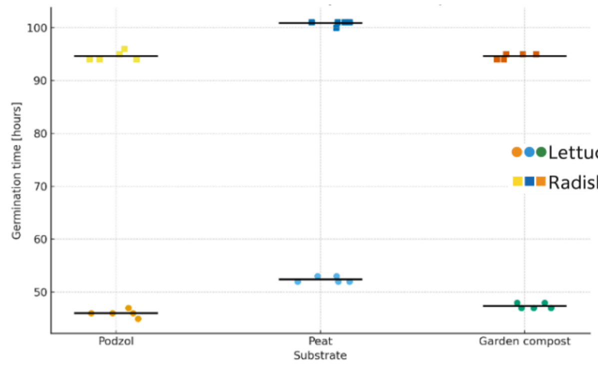

Fig. 5 – Seed germination time by substrate

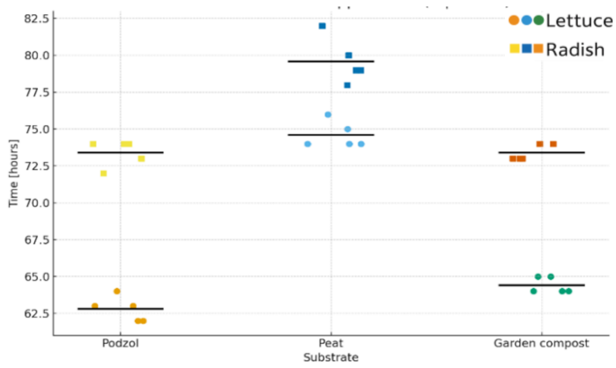

Fig. 6 – Time of first true leaf appearance

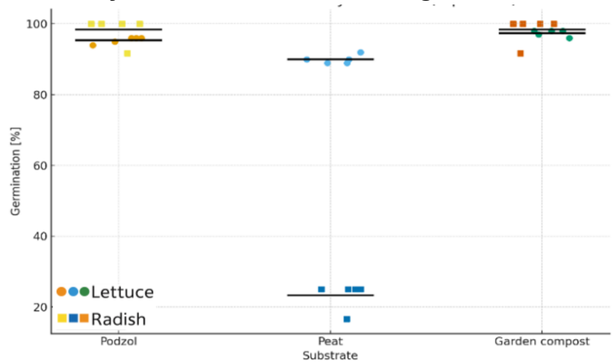

Fig. 7 – Seed germination rate by substrate

Table 5 presents the consolidated results of germination dynamics and early plant development for lettuce and radish grown in the three tested substrates (garden compost, peat, and podzol). The data are expressed as mean values ± standard deviation, based on 15 replicates per treatment. The parameters included are germination time, time to first true leaf appearance, and germination rate, allowing a comparative assessment of how substrate quality influences seed performance and early growth.

Table 5

Comparative germination and early growth performance (mean ± std) of lettuce and radish in peat, garden compost, and podzol

Substrate	Plant type	Germination time		Leaf appearance time		Germination rate	
		mean	std	mean	std	mean	std
Garden compost	Lettuce	47.4	0.55	64.4	0.55	97.4	0.89
Garden compost	Radish	94.6	0.55	73.4	0.55	98.34	3.71
Peat	Lettuce	52.4	0.55	74.6	0.89	90.0	1.22
Peat	Radish	100.8	0.45	79.6	1.52	23.33	3.73
Podzol	Lettuce	46.0	0.71	62.8	0.84	95.4	0.89
Podzol	Radish	94.6	0.89	73.4	0.89	98.34	3.71

The results highlight clear differences between substrates and plant species. For lettuce, both germination time and leaf appearance time were shortest in podzol (46.0 ± 0.71 h and 62.8 ± 0.84 h, respectively), with a high germination rate (95.4 ± 0.89%). Garden compost showed similar performance, with slightly longer times but a germination rate close to 97%. In contrast, peat delayed both germination (52.4 ± 0.55 h) and leaf emergence (74.6 ± 0.89 h), and reduced germination success to 90%.

For radish, the contrast was even stronger. Both podzol and compost provided short germination and true leaves appearance times (≈94–95 h and ≈73 h, respectively), with very high germination rates (≈98%). However, in peat, germination was significantly delayed (100.8 ± 0.45 h), leaf appearance was extended to 79.6 ± 1.52 h, and germination success dropped drastically to only 23.3 ± 7.3%.

These results confirm that peat is a poor substrate for radish due to its low water retention and unfavourable physical properties, while garden compost and podzol provided optimal conditions for both species.

An indirect relationship was observed between substrate nutrient values and seed germination: compost and podzol, which contained higher N–P–K levels, supported faster and more uniform germination, while peat—with minimal nutrient content—produced delayed and reduced germination. This suggests that the main nutrient content, together with moisture and density, acted as a composite qualitative index of substrate suitability for seedling establishment.

To further investigate the relationships between germination dynamics and early plant development, correlation analyses were performed between germination time, leaf appearance time, and germination rate for lettuce and radish across all three substrates. Scatter plots with linear regression lines (Figures 8-10) illustrate how delays in one stage of development may influence subsequent growth stages or overall germination success. These correlations provide deeper insight into the extent to which substrate quality affects not only absolute values of germination and growth parameters, but also the interdependence between them.

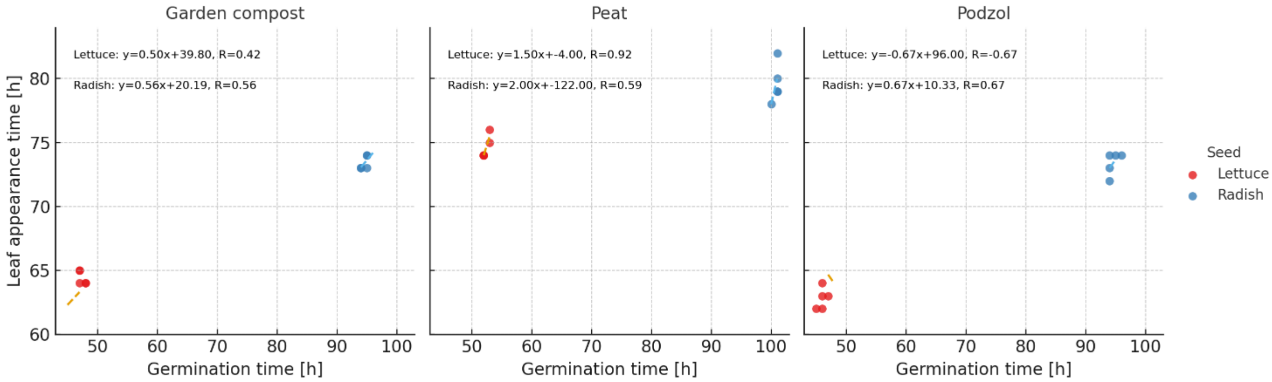

Fig. 8 – Correlation between germination time and true leaf appearance time for the substrates used

The relationship between germination time and leaf appearance time highlights how delays in the initial phase of development propagate into subsequent growth stages. A strong positive correlation was observed in lettuce grown on peat (R ≈ 0.92), indicating that slower germination was consistently followed by delayed leaf emergence. Radish exhibited similar positive trends across substrates, with R values between 0.56 and 0.67. In contrast, lettuce grown in garden compost showed a negative correlation (R ≈ –0.67), suggesting that even seeds germinating later were able to compensate and produce leaves within a normal time frame, likely due to improved nutrient and water availability from the soil's natural characteristics.

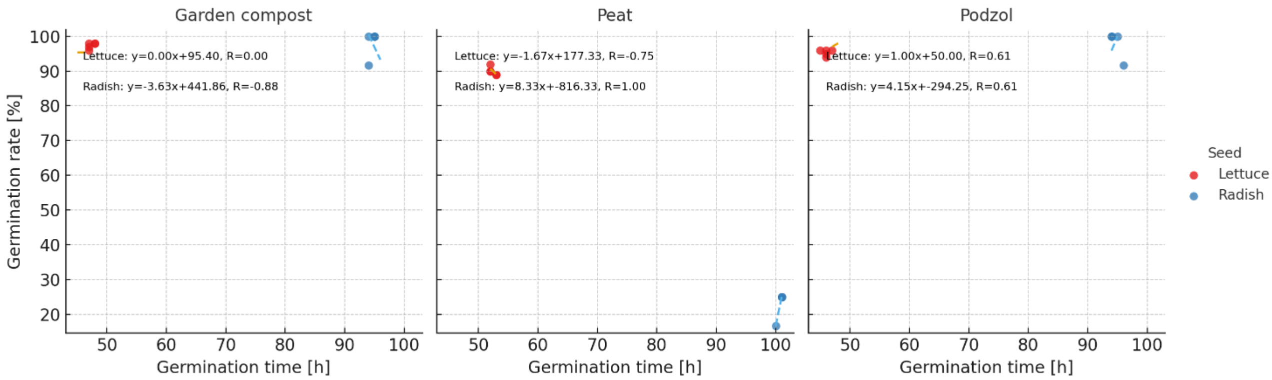

Fig. 9 – Correlation between germination rate and germination time for the substrates used

This correlation reveals how the speed of germination is linked to overall success rates. In lettuce grown on peat and radish grown on podzol, strong negative correlations (R ≈ –0.75 and –0.87, respectively) demonstrate that prolonged germination times substantially reduced the number of seeds completing germination. By contrast, garden compost showed moderate positive relationships (R ≈ +0.6), indicating that late-germinating seeds could still succeed, reflecting the substrate's ability to overcome stress conditions. Radish grown on peat displayed an apparent perfect correlation (R = +1.00), but this reflects the very low and uniform germination rates in this treatment.

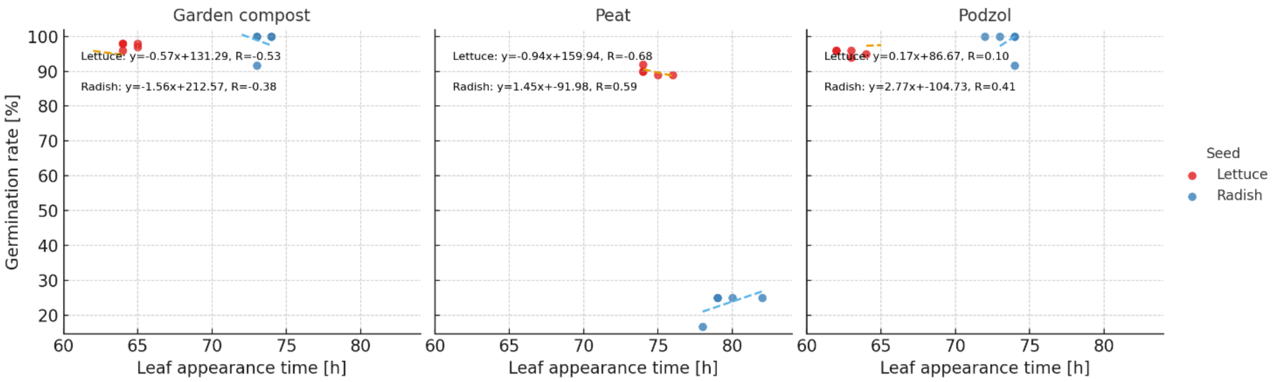

Fig. 10 – Correlation between germination rate and true leaf appearance time for the substrates used

The time of true leaf emergence was also influenced by the germination success. For lettuce, later leaf appearance was associated with lower germination rates, particularly in peat (R ≈ –0.68) and, to a lesser extent, in podzol (R ≈ –0.53). This pattern suggests that early leaf development is a key indicator of vigour in lettuce. Radish, however, displayed positive correlations in peat and compost (R ≈ 0.4–0.6. These results underline that lettuce is more sensitive to early developmental delays, while radish shows greater resilience when grown in compost substrate.

The results obtained in this study confirmed that substrate composition strongly influences both germination time and success rate. Lettuce showed relatively stable germination across all substrates, though peat caused moderate delays due to its lower moisture retention and nutrient content. Similar observations were reported by *Hernández-Rodríguez et al. (2017)*, who found that mixing peat with semi-compost or vermicompost significantly improved lettuce germination and seedling vigour compared with pure peat. For radish, the differences were more pronounced—compost and podzol supported rapid, uniform germination with rates above 95%, while peat reduced germination to below 25%. These findings align with the results of *Neofytou et al. (2024)*, who observed enhanced early growth of *Raphanus sativus* seedlings when phosphorus availability and organic matter levels were higher, and with *Warman and Anglopez (2010)*, who reported that nutrient-rich vermicompost substrates produced stronger radish emergence than peat-based media. Comparable trends were also noted by *Kollárová et al. (2025)*, demonstrating that substrate–genotype interactions substantially affect germination rate and early growth dynamics in microgreens.

For radish, both delayed emergence and a drastic reduction in germination percentage were observed on peat, while compost and podzol supported high and synchronous germination. Literature on radish indicates that substrate effects can vary with system: in microgreens production, germination rates were statistically similar on sphagnum peat and coco coir, although fresh yield differed (*Thuong and Minh, 2020*); conversely, some vermicompost–peat mixes can suppress radish germination if not used at suitable ratios (*Warman et al., 2010*). These reports together suggest that substrate chemistry (pH/EC), maturity, and water/air relations interact strongly with species and production system, which can reconcile the higher sensitivity measured for radish under the conditions employed in this study.

Differences among studies often reflect compost maturity. The germination index (GI), introduced by Zucconi et al., is a widely adopted bioassay for compost phytotoxicity/maturity; GI values ≳60% generally indicate mature, non-toxic compost (*Paradelo and Barral, 2011; Zucconi et al., 1981*). Reviews and recent work confirm GI as a sensitive, operational indicator across compost types (*Bernal et al., 2009; Lončarić et al., 2024*). Ensuring mature compost helps explain why compost/podzol treatments in this study maintained both high germination and shorter germination times, whereas peat (nutrient-poor, acidic) performed poorly, especially for radish seeds.

CONCLUSIONS

The experimental research carried out with the intelligent plant growth simulation system confirmed that substrate type exerts a decisive influence on the germination dynamics and early development of seeds in controlled conditions. Lettuce showed generally high germination rates across all substrates, though germination and leaf appearance were delayed in peat. Radish proved far more sensitive: while compost and podzol provided rapid and synchronous germination with high success rates, peat severely reduced germination percentages and delayed both emergence and leaf development.

Correlation analyses provided further insights into these dynamics. In lettuce grown on peat, strong positive relationships between germination time and leaf appearance time indicated that delays in the initial phase propagate throughout early development. Negative correlations between germination rate and germination time in lettuce (peat) and radish (podzol) highlighted how prolonged germination reduces overall success, while the more favourable nutrient and moisture regimes of compost buffered these effects. These results underline the importance of selecting appropriate substrates to achieve both uniformity and high efficiency in seedling establishment.

The results can provide useful guidance for both growers and developers of controlled-environment agriculture systems. The clear differences between substrates indicate that peat, while traditionally used, is not suitable for radish production under controlled conditions, whereas compost and podzol offer reliable performance. This knowledge can support substrate selection in greenhouses, growth chambers, and vertical farming systems, helping practitioners reduce losses associated with poor germination and uneven seedling stands.

Future research should extend these experiments to a wider range of crop species and substrate blends, including engineered mixes with biochar, perlite, or other soil conditioners that may further optimize water retention and aeration.

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