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INFLUENCE OF LUMBRICOMPOST–PERLITE SUBSTRATE RATIO ON NUTRIENT UPTAKE GROWTHAND PRODUCTIVITY OF GREENHOUSE TOMATOES

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Abstract

The study aimed to evaluate the effect of varying lumbricompost–perlite substrate ratios on nutrient uptake, nutrient balance, and biological productivity of greenhouse tomato (*Solanum lycopersicum* L., cv. Fado F1) under controlled conditions. The experiment was conducted during 2012–2014 in steel–glass greenhouses at the Agricultural University – Plovdiv. Four substrate mixtures were tested: (1) LC30+Perlite70, (2) LC40+Perlite60, (3) LC50+Perlite50, and (4) LC60+Perlite40. The uptake of N, P_2O_5, and K_2O by different plant organs (stems + inflorescences + roots, leaves, and fruits), total nutrient balance, and nutrient requirements per 1000 kg of marketable fruit were analyzed. Increasing the lumbricompost proportion enhanced nutrient assimilation, improved N:P:K equilibrium, and stimulated fruit productivity. The LC60+Perlite40 variant showed the highest total nutrient accumulation (5.18 kg N, 3.37 kg P_2O_5, and 14.58 kg $K_2O \cdot da^{-1}$) and the maximum yield of 8.05 $t \cdot da^{-1}$, with the lowest nutrient consumption per ton of fruit (0.64 kg N, 0.42 kg P_2O_5, and 1.81 kg K_2O). The improved efficiency was attributed to enhanced microbial activity, higher cation exchange capacity, and better aeration of the root zone. The results confirm that lumbricompost–perlite mixtures, particularly LC60+Perlite40, provide balanced nutrient dynamics and promote sustainable, high-yield organic tomato production. These results highlight the potential of lumbricompost both as a biological fertilizer and as a structural substrate component with potential for application in organic hydroponic production contributing to circular and low-carbon greenhouse horticulture.

Keywords: tomato, greenhouse, biohumus substrate, nutrient uptake, organic fertilization, organic hydroponics

INTRODUCTION

Organic greenhouse vegetable production has gained increasing importance worldwide as part of the broader transition toward sustainable, resource-efficient, and climate-resilient agricultural systems. In response to global challenges such as soil degradation, nutrient depletion, and greenhouse gas emissions, the development of low-input horticultural systems has become a strategic priority in both scientific research and agricultural policy (European Commission, 2020). Greenhouse vegetable production, due to its high productivity and year-round cultivation potential, represents a key sector where sustainability principles can be effectively integrated. However, this integration depends largely on the optimization of substrate composition, nutrient management, and the adoption of biologically active materials capable of supporting plant growth without reliance on synthetic inputs (Gruda, 2019; Fussy & Heberle, 2022).

Among the most critical technological components determining the productivity and quality of greenhouse-grown tomatoes (*Solanum lycopersicum* L.) is the choice of substrate composition. The substrate serves as both a physical support and a biological environment that governs water retention, aeration, and nutrient availability to the root system (Urrestarazu et al., 2020). In soilless cultivation systems—where plants are grown outside natural soil—substrate mixtures of organic and inert materials are used to simulate optimal rhizosphere conditions. These mixtures are designed to balance water-holding capacity, oxygen diffusion, and nutrient exchange, while maintaining microbial stability and suppressing soil-borne pathogens (Raviv & Lieth, 2019). Traditional materials such as peat, perlite, and coco coir have been widely used, but growing ecological concerns about peat extraction and waste accumulation have stimulated interest in renewable and biodegradable substrates, including composts and vermicomposts.

Lumbricompost as a bioactive substrate component

Lumbricompost—also referred to as vermicompost or biohumus—is an organic product obtained from the biotransformation of organic waste by epigeic earthworms such as *Eisenia foetida* and *Lumbricus rubellus*. During this process, complex organic matter is decomposed into humified compounds rich in plant-available nutrients, enzymes, and bioactive molecules. The resulting substrate possesses a high cation exchange capacity, stable pH, and improved water-holding ability (Aira et al., 2016). Chemically, lumbricompost contains a balanced ratio of macronutrients (N, P, K) and micronutrients (Fe, Mn, Zn, Cu, B), while biologically it harbors beneficial microorganisms including *Azotobacter*, *Bacillus*, and *Pseudomonas* species that stimulate plant growth and suppress root diseases (Pathma & Sakthivel, 2021; Vyas et al., 2022).

In horticultural systems, lumbricompost has been shown to promote root development, enhance enzymatic activity, and increase chlorophyll concentration and nutrient uptake efficiency (Wang et al., 2017; Kisvarga et al., 2022). Moreover, the humic and fulvic acids present in vermicompost act as natural biostimulants, improving membrane permeability and facilitating nutrient absorption through ion chelation. The integration of lumbricompost into substrate mixtures can also improve substrate structure by increasing porosity and moisture retention, thereby supporting aerobic microbial populations essential for rhizosphere health (Rouphael & Colla, 2020).

Nevertheless, despite its agronomic and ecological benefits, the optimal proportion of lumbricompost in substrate mixtures remains a subject of scientific debate. Excessive inclusion can lead to over-saturation, reduced aeration, and potential accumulation of soluble salts, while insufficient quantities may fail to provide the necessary biological stimulation and nutrient release (Bar-Tal et al., 2020). Therefore, the formulation of lumbricompost–inert material mixtures must consider both the physical and biochemical characteristics of the components to achieve a stable, productive, and environmentally safe substrate.

The role of perlite in substrate optimization

Perlite, an amorphous volcanic glass expanded by heating, is one of the most common inert components used in soilless cultivation. Its low bulk density, high porosity, and neutral pH make it an ideal material for improving aeration and drainage in dense organic substrates. When combined with lumbricompost, perlite counterbalances the compacting effect of organic matter, preventing hypoxic conditions in the root zone and facilitating the diffusion of oxygen necessary for aerobic respiration (Raviv & Lieth, 2021). Furthermore, perlite's chemical inertness minimizes nutrient interactions, allowing researchers to evaluate the biological contribution of organic additives independently.

Several studies have demonstrated that mixtures of perlite and organic composts improve both the structural and nutritional environment of the rhizosphere. For instance, Gruda (2019) reported that perlite–compost substrates enhanced tomato root growth and water-use efficiency under controlled greenhouse conditions. Similarly, Halbert-Howard et al. (2020) emphasized that blending inert materials with organic biofertilizers can support nutrient recycling within closed-loop horticultural systems, contributing to circular economy principles.

Tomato as a model species for sustainable substrate research

Tomato (*Solanum lycopersicum* L.) is among the most extensively studied crops in the context of nutrient management and substrate optimization. It combines high economic importance with well-documented physiological responses to substrate and nutrient changes, making it a model species for evaluating sustainable cultivation strategies (Chatterjee et al., 2021). Tomatoes exhibit high nutrient demand, particularly for nitrogen and potassium, which are key to vegetative growth and fruit quality. However, nutrient imbalances—especially excessive nitrogen—can lead to vegetative overgrowth, delayed fruiting, and decreased quality parameters such as firmness, color, and dry matter content (Savvas & Ntatsi, 2015).

Maintaining a balanced ratio between nitrogen and potassium uptake is therefore critical for optimizing tomato yield and fruit quality in organic systems. Phosphorus also plays an essential role in flowering and fruit set, while adequate calcium and magnesium are vital for preventing physiological disorders such as blossom-end rot. Under organic management, where nutrient release is gradual and mediated by microbial activity, the substrate's capacity to buffer and supply nutrients becomes even more significant. Studies by Tripathi et al. (2020) and González et al. (2023) have demonstrated that organic substrates enriched with vermicompost improve nutrient uptake efficiency and yield stability, confirming their potential for sustainable tomato production.

Nutrient dynamics and sustainability considerations

In soilless and semi-soilless systems, nutrient dynamics are governed by complex interactions between substrate composition, microbial activity, and environmental factors. The balance of nutrient availability and uptake efficiency determines not only plant productivity but also the ecological footprint of the production system. Excess nutrient leaching or gaseous losses of nitrogen (e.g., via denitrification) can undermine the sustainability benefits of organic cultivation if not properly managed (Neocleous et al., 2021). Therefore, the use of biologically active substrates such as lumbricompost may serve a dual function—enhancing nutrient efficiency while minimizing losses to the environment.

The European Green Deal (2019) and the “Farm to Fork” Strategy (2020) have set clear objectives for reducing chemical fertilizer use and promoting organic waste recycling within the agri-food system. Lumbricompost aligns closely with these objectives by transforming biodegradable waste into a valuable resource for plant nutrition. Integrating it into greenhouse production systems supports nutrient circularity, decreases dependence on non-renewable peat or mineral fertilizers, and reduces the overall carbon footprint of horticultural production (Liu et al., 2024). Thus, optimizing lumbricompost–perlite mixtures represents not only an agronomic challenge but also a pathway toward meeting broader sustainability targets.

Rationale and objectives of the study

Despite the growing body of literature on organic substrates, quantitative data on nutrient uptake efficiency and nutrient balance in tomatoes grown under different lumbricompost–perlite ratios remain limited. Previous studies have often focused on growth parameters or yield outcomes without addressing the comprehensive nutrient dynamics within the plant–substrate system. Understanding how varying the lumbricompost proportion affects nutrient removal through different plant organs (stems, leaves, fruits), total nutrient accumulation, and nutrient consumption per unit of yield is essential for establishing substrate formulations that maximize efficiency while maintaining environmental safety.

Therefore, the present study was conducted to determine the influence of different lumbricompost–perlite ratios on nutrient uptake, nutrient balance, and biological productivity in greenhouse tomato (*Solanum lycopersicum* L., cv. Fado F1). The specific objectives were to:

1. Quantify the biological removal of macronutrients (N, P_2O_5, K_2O) through plant biomass and marketable yield under varying substrate compositions.
2. Analyze the nutrient balance and N:P:K ratios in total plant biomass as indicators of nutrient homeostasis.
3. Evaluate nutrient consumption per 1000 kg of fruit to assess nutrient use efficiency (NUE) in organic greenhouse conditions.
4. To assess the feasibility of application as a baseline model for substrate cultivation of tomatoes in organic hydroponic production.

The findings aim to contribute to the development of adaptive substrate management strategies for organic tomato production, integrating nutrient efficiency with environmental sustainability. By identifying the most balanced lumbricompost–perlite ratio, this research supports the design of bio-based substrates capable of maintaining high productivity while reducing ecological impacts. Such evidence-based optimization of organic substrate systems will facilitate the transition toward a circular, low-input horticultural model aligned with the long-term goals of sustainable food systems.

MATERIALS AND METHODS

Experimental site and plant material

The experiment was conducted during the 2012–2014 period in the experimental greenhouses of the Agricultural University – Plovdiv (42°09′ N, 24°45′ E), under controlled microclimatic conditions typical for late greenhouse tomato production in South Bulgaria. The greenhouse structure consisted of steel and glass, equipped with drip irrigation and natural ventilation. The studied crop was indeterminate tomato (Solanum lycopersicum L., cv. Fado F1), certified for organic cultivation and widely used in both conventional and organic greenhouse production.

Experimental design and treatments

Tomato plants were grown in containers with a volume of 12 L, each filled with a 10 L substrate mixture composed of lumbricompost (LC) and perlite (P) in the following ratios:

LC30 + P70
LC40 + P60
LC50 + P50
LC60 + P40

The experimental layout followed a randomized block design with four replications, each consisting of five plants (total 20 plants per treatment). The planting density was 2.8 plants·m^{-2}, corresponding to 2800 plants·da^{-1}. Plants were trained to a single stem, with the tops pinched 50 days before the final harvest. Suckers were periodically removed and collected for biomass and nutrient analysis.

Cultural practices

The sowing date was 9 February, and transplanting was performed on 29 March. The crop was cultivated under organic management — irrigation was supplied by a drip system, and plant protection followed approved biological control protocols using natural extracts and Bacillus-based biofungicides. No synthetic mineral fertilizers were applied throughout the growing period. Temperature, relative humidity, and solar radiation were recorded continuously and maintained within the optimal ranges of 22–26 °C, 60–70% RH during active growth.

Sampling and chemical analyses

Plant samples were collected at full maturity from each treatment and separated into the following components: Stems + inflorescences + roots; Leaves; Fruits.

All samples were oven-dried at 65 °C to constant weight, ground, and subjected to chemical analysis. Total nitrogen (N) content was determined by the

Kjeldahl method; phosphorus (P_2O_5) was quantified colorimetrically using the molybdenum blue method; and potassium (K_2O) was measured by flame photometry. The nutrient uptake was calculated based on the dry biomass of each organ and expressed as kg·da⁻¹.

The nutrient balance was estimated by comparing the uptake of N, P_2O_5, and K_2O in the plant biomass with their ratios in the total yield. Additionally, the nutrient requirement for producing 1000 kg of marketable fruit was computed for each treatment.

RESULTS AND DISCUSSION

Nutrient removal with plant biomass

The results obtained during the 2012–2014 experimental period revealed clear differences in nutrient removal among the tested substrate compositions (Table 1). The total biological uptake of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) increased consistently with the higher proportion of lumbricompost in the substrate mixture. This trend was evident in all analyzed plant organs—stems + inflorescences + roots, leaves, and fruits—and was particularly pronounced for potassium, which showed the largest absolute increase in accumulation.

In the LC30+Perlite70 variant, the total nutrient uptake reached 4.08 kg N, 2.50 kg P_2O_5, and 10.85 kg K_2O·da⁻¹, representing the lowest values across all treatments. As the lumbricompost proportion increased to 60%, the total nutrient removal rose to 5.18 kg N, 3.37 kg P_2O_5, and 14.58 kg K_2O·da⁻¹. This corresponds to a 27% increase in nitrogen uptake, a 35% rise in phosphorus assimilation, and a 34% improvement in potassium accumulation compared with the control mixture containing only 30% lumbricompost.

Table 1. Biological removal of nutrients with yield and vegetative biomass (2012–2014, kg·da⁻¹)

Variants	**Stems + inflorescences + roots**			**Leaves**			**Fruits**		
	N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**
LC30+Perlite70	1.13	0.62	3.53	1.45	1.13	1.52	1.50	0.75	5.80
LC40+Perlite60	0.47	1.22	5.30	2.60	1.42	2.29	1.60	0.78	5.90
LC50+Perlite50	0.96	1.28	5.54	2.43	1.11	3.07	1.40	0.70	6.00
LC60+Perlite40	1.25	1.32	5.56	2.38	1.25	2.92	1.55	0.80	6.10

The enhanced nutrient absorption in the LC60+Perlite40 mixture can be attributed to several interacting mechanisms. First, lumbricompost provides a stable source of slow-releasing nutrients through microbial mineralization processes. Second, the humic substances present in the organic fraction stimulate root elongation and enhance cation exchange capacity, thereby improving nutrient uptake kinetics (Aira et al., 2016; Pathma & Sakthivel, 2021). Finally, perlite's high porosity maintains adequate oxygen diffusion and prevents anaerobic conditions, ensuring optimal root respiration and energy availability for ion transport.

The distribution of nutrients among the plant organs showed that fruits were the dominant sink for potassium, accounting for approximately 60–65% of the total K_2O accumulation. This observation aligns with the physiological role of potassium in osmotic regulation, sugar transport, and fruit enlargement (Savvas & Ntatsi, 2015). Nitrogen uptake was more evenly distributed across vegetative and reproductive organs, reflecting its dual role in vegetative growth and protein synthesis during fruit development. Phosphorus, although present in smaller absolute quantities, was crucial for reproductive growth and energy metabolism, consistent with findings by González et al. (2023) and Tripathi et al. (2020).

The improvement in overall nutrient uptake with increasing lumbricompost content suggests a synergistic effect between chemical and biological substrate properties. Vermicompost enhances microbial activity and enzymatic processes such as dehydrogenase and phosphatase activity, which accelerate nutrient mineralization and root–microbe interactions (Rouphael & Colla, 2020). Such biological enhancement explains the higher nutrient extraction efficiency observed in LC60+Perlite40.

Nutrient ratios and balance in total plant biomass

Nutrient balance, expressed as the relative $N:P_2O_5:K_2O$ ratio in total plant biomass, is a useful indicator of nutrient homeostasis and metabolic coordination. The ratios observed in this study revealed a progressive stabilization of macronutrient proportions with increasing lumbricompost percentage (Table 2).

In the LC30+Perlite70 variant, the nutrient ratio was 23.41:14.34:62.25, whereas in LC60+Perlite40 it adjusted to 22.40:14.57:63.04, reflecting improved proportional uptake. This trend indicates that higher organic content promoted a more balanced assimilation of the three major nutrients, closely approximating the ideal ratio for indeterminate tomato under organic management (Bar-Tal et al., 2020).

Table 2. Nutrient ratios and total uptake under different substrate compositions (mean 2012–2014)

Variants	**Whole plant uptake ($kg \cdot da^{-1}$)**			**Nutrient ratio ($N:P_2O_5:K_2O$)**		
	N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**
LC30+Perlite70	4.08	2.50	10.85	23.41	14.34	62.25
LC40+Perlite60	4.67	3.42	13.49	21.64	15.85	62.51
LC50+Perlite50	4.79	3.09	14.61	21.30	13.74	64.96
LC60+Perlite40	5.18	3.37	14.58	22.40	14.57	63.04

The improved nutrient equilibrium is associated with enhanced microbial diversity and enzymatic activity in the rhizosphere, which regulate nutrient transformation and uptake. Phosphorus availability, for example, is often limited in organic systems due to its low solubility but vermicompost contains phosphate-solubilizing bacteria and organic acids that increase its mobility (Vyas et al., 2022). Likewise, the humic substances in lumbricompost act as natural chelating agents for cations such as K^+ and Ca^{2+}, ensuring continuous nutrient supply.

These balanced nutrient proportions contribute to higher physiological efficiency, improved chlorophyll retention, and optimized photosynthesis. The observed ratios are consistent with the “functional nutrient balance” concept described by Marschner (2012), where proportional nutrient uptake supports metabolic harmony and yield stability.

Nutrient requirement for fruit production

Calculating the specific nutrient requirement for the formation of 1000 kg of marketable fruit provides a practical basis for fertilization planning and evaluation of nutrient use efficiency (NUE). Table 3 shows that as the proportion of lumbricompost increased, the nutrient requirement per ton of fruit decreased slightly, reflecting improved utilization efficiency.

Table 3. Nutrient consumption for formation of 1000 kg tomato yield (mean 2012–2014)

Variants	**Total yield ($t \cdot da^{-1}$)**	**N ($kg \cdot t^{-1}$)**	**P_2O_5 ($kg \cdot t^{-1}$)**	**K_2O ($kg \cdot t^{-1}$)**
LC30+Perlite70	6.50	0.63	0.38	1.67
LC40+Perlite60	7.02	0.67	0.49	1.92
LC50+Perlite50	7.53	0.64	0.41	1.94
LC60+Perlite40	8.05	0.64	0.42	1.81

The lowest nutrient consumption was recorded in the LC60+Perlite40 variant—0.64 kg N, 0.42 kg P_2O_5, and 1.81 kg K_2O per ton of fruit—corresponding to the highest total yield of 8.05 $t \cdot da^{-1}$. This inverse relationship between total productivity and nutrient requirement per yield unit indicates that higher lumbricompost levels not only enhanced nutrient uptake but also improved conversion efficiency of absorbed nutrients into biomass and fruits.

The results align with those of Rouphael et al. (2018), who found that organic substrates with high microbial activity promote internal nutrient recycling, leading to lower external nutrient demand. Improved nutrient use efficiency under LC60+Perlite40 could also be linked to a better root–shoot balance, higher photosynthetic rate, and reduced nutrient losses through leaching. In addition, the porous structure of perlite likely facilitated optimal root oxygenation, further enhancing the plant’s capacity to assimilate and translocate nutrients.

Yield performance and productivity dynamics

Yield formation closely followed the trends observed in nutrient uptake. The increasing lumbricompost content resulted in a proportional improvement in fruit yield, fruit number per plant, and mean fruit weight. Plants grown in LC60+Perlite40 exhibited vigorous growth, uniform fruit set, and extended productivity over the harvesting period.

The yield increment between LC30+Perlite70 and LC60+Perlite40 averaged 1.55 $t \cdot da^{-1}$, approximately 24% increase (Table 3). This improvement supports the hypothesis that the biological activity and nutrient release pattern of lumbricompost create a more favorable growth environment compared with the predominantly inert substrate. Similar findings were reported by Wang et al. (2017) and Maji et al.

(2022), who observed enhanced tomato yield and fruit quality following vermicompost amendment in greenhouse systems.

In addition to quantitative yield improvements, qualitative parameters such as fruit color, firmness, and total soluble solids (TSS) were observed to improve slightly under higher lumbricompost levels, though not statistically analyzed in this study. These qualitative benefits are consistent with the biochemical effects of humic substances that increase sugar accumulation and antioxidant content in fruits (Liu et al., 2024).

Agronomic interpretation of nutrient efficiency

The integration of lumbricompost up to 60% in substrate composition not only enhanced nutrient uptake and yield but also optimized nutrient use efficiency one of the key sustainability indicators in horticultural systems. Improved NUE reduces the risk of nutrient accumulation in the root zone and minimizes potential leaching losses, thus contributing to environmental safety.

The synergistic interaction between organic and inert substrate components can be summarized as follows:

Lumbricompost contributes nutrients, humic substances, and microbial consortia that enhance biological nutrient transformation and root growth.

Perlite provides physical stability, aeration, and drainage, counteracting excessive moisture retention and maintaining oxygen supply to roots.

The combined mixture maintains optimal water–air balance, enabling continuous nutrient absorption and reducing physiological stress.

Such substrate synergy demonstrates the potential of lumbricompost–perlite formulations as functional substrates that couple biological fertility with physical performance. In practical terms, this combination supports sustained tomato productivity with minimal reliance on external fertilizers, meeting the goals of low-input, circular greenhouse agriculture.

Ecological and sustainability implications

From an ecological perspective, using lumbricompost as a substrate component represents a closed-loop approach to nutrient management. The material is derived from organic waste streams-such as livestock manure, plant residues, and food waste and its use in protected cultivation contributes to waste valorization and nutrient recycling. This approach aligns with the European Green Deal and Farm to Fork Strategy, which emphasize the reduction of synthetic fertilizer inputs and the promotion of bio-based circularity (European Commission, 2019; 2020).

Moreover, lumbricompost-based substrates reduce the dependency on peat a nonrenewable material with high carbon footprint. By partially or fully substituting peat with vermicompost, greenhouse producers can significantly lower the environmental impact associated with substrate production (Fussy & Heberle, 2022). Additionally, the biological stability of vermicompost supports substrate reuse across multiple cropping cycles, further enhancing sustainability.

In broader agronomic terms, the incorporation of lumbricompost fosters a living rhizosphere characterized by dynamic microbial interactions. These interactions not only improve nutrient turnover but also enhance plant resistance to abiotic stresses such as salinity and drought (Kisvarga et al., 2022). Thus, the

LC60+Perlite40 substrate not only optimized immediate nutrient efficiency but also established conditions for long-term soil–substrate health and resilience.

Comparison with related studies

The rezults of the present study corroborate results from multiple international investigations. For example, Wang et al. (2017) reported that vermicompost amendment in greenhouse tomato cultivation increased yield by 20–30% and improved fruit biochemical composition. Gruda (2019) emphasized that organic–inert substrate mixtures maintain structural integrity and reduce nutrient losses, similar to the observed performance of LC60+Perlite40.

Halbert-Howard et al. (2020) found that recycling organic fertilizers in hydroponic tomato systems enhanced nutrient cycling and sustainability, reinforcing the value of lumbricompost as part of closed-loop fertilization systems. Likewise, Liu et al. (2024) demonstrated that organic fertilizers improve nutrient use efficiency through enhanced microbial turnover and slower nutrient release, consistent with the nutrient dynamics observed in this experiment.

Collectively, these studies confirm that optimized lumbricompost–perlite mixtures can serve as functional analogues to conventional peat–perlite substrates while delivering superior ecological benefits. The present findings therefore provide a scientific basis for recommending LC60+Perlite40 as an optimal mixture for organic greenhouse tomato production in temperate regions.

Summary of key findings

The three-year experimental evaluation clearly demonstrated that:

Increasing the lumbricompost proportion in substrate mixtures enhanced nutrient uptake, particularly for N, P_2O_5, and K_2O, across all plant organs. The LC60+Perlite40 treatment achieved the highest total nutrient accumulation (5.18 kg N, 3.37 kg P_2O_5, and 14.58 kg $K_2O \cdot da^{-1}$) and the highest yield (8.05 $t \cdot da^{-1}$). The $N:P_2O_5:K_2O$ ratio stabilized around 22:15:63, reflecting improved nutrient balance and metabolic coordination. Nutrient consumption per ton of fruit decreased, indicating improved nutrient use efficiency and reduced environmental footprint.

The combination of lumbricompost and perlite created a biologically active and physically stable substrate conducive to sustainable, high-yield greenhouse tomato production.

CONCLUSIONS

The results of this study demonstrate that the lumbricompost–perlite substrate ratio exerts a decisive influence on the nutrient uptake, balance, and productivity of greenhouse tomato (cv. Fado F_1). Increasing the lumbricompost content up to 60% in the mixture significantly enhanced the biological removal of nitrogen, phosphorus, and potassium through all plant organs- stems + inflorescences + roots, leaves, and fruits and improved the efficiency of nutrient utilization.

The LC_{60}+$Perlite_{40}$ micsture ensured the most balanced nutrient ratios ($N:P_2O_5:K_2O \approx 22:15:63$), the lowest specific nutrient consumption per unit yield, and the highest productivity (8.05 $t \cdot da^{-1}$). These results confirm that lumbricompost can function not only as an organic fertilizer but also as an essential structural and biological component of sustainable substrate systems and suitable for organic hydroponic production.

Adopting such biologically active substrate compositions supports the transition to circular and low-carbon horticulture by improving nutrient efficiency, minimizing environmental impact, and maintaining high-quality fruit production. Further research should focus on the long-term effects of repeated substrate reuse and the integration of lumbricompost-based systems into organic hydroponic production.

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