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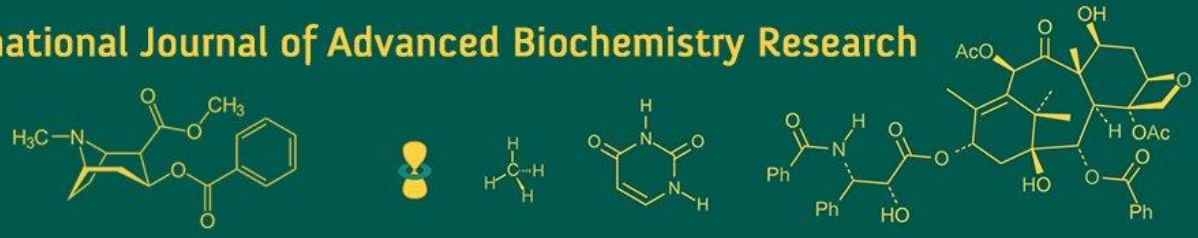

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Assessment of morphophysiological and growth characteristics of *Capsicum annuum* L.: A Vermiponic cultivation approach

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Abstract
An alternative prospective strategy for sustainable crop production through soilless culture is to utilise resource efficiency and overcome constraints posed by soil. Vermiponics, wherein vermiwash (VW) is used in hydroponic farming, offers an organic way to enhance plant growth and yield. The present study evaluated the effect of growth characteristics of chilli (*Capsicum annuum* L.) under a non-circulating vermiponics system in out-door conditions. Thirteen treatments under 5% and 10% vermiwash (VW) concentrations were evaluated in combination with different organic substrates vermicompost (VC), farmyard manure (FYM), rice husk ash, and cocopeat in comparison to the control fed with water, under a completely randomized design. At 40 and 60 days after transplanting, remarkable enhancements in growth parameters were recorded. Significant differences in growth were noted 60 days after transplanting, with T_8 (VC+ FYM+ Rice husk ash (2:1:1) + 10% VW) displaying the tallest plants, T_1 (VC + 5% VW) the highest number of leaves, and T_6 (VC+ FYM+ Cocopeat (2:1:1) + 10% VW) the longest roots. Plants flowered early in T_8 at 40 days, whereas control plants did not flower at all. These findings indicate that vermiwash functions both as a nutrient-rich fertilizer and a biostimulant, thereby positioning vermiponics as a sustainable alternative for the cultivation of chili within urban environments and small-scale residential agricultural systems.

Keywords: Vermiponics, soilless cultivation, vermicompost, hydroponics, vermiwash

Introduction
Currently, agricultural ventures are subjected to the predominant challenge of meeting the nutritional needs of a growing population while also reducing adverse environmental impact. The global population is expected to reach nearly 10 billion by 2050, which will intensify the pressure on already limited land and water resources. (Tilman *et al.*, 2002; Sambo *et al.*, 2019) [3, 2]. Traditional farming methods have been effective in boosting yields, but have resulted in subsequent soil degradation, water shortages, and greenhouse gas emissions. These issues raise concerns about the long-term sustainability of such practices. There is an evident necessity for new farming systems that promote efficient resource use, protect the environment, and ensure consistent crop productivity for ensuring future food security prospects at various levels.

Among various methods, soilless farming systems, especially hydroponics (HP), has emerged as a practical supplement to conventional agriculture. HP systems offer controlled nutrient delivery and bypasses soil-related issues. This leads to optimized nutrient-use efficiency, water use economics and enabling of year-round farming prospects, even in areas where soil is not suitable for crop cultivation, particularly in urban establishments (Khatun *et al.*, 2022; Sambo *et al.*, 2019) [1, 2]. Globally, HP currently makes up about 3.5 per cent of vegetable production in protected cultivation platforms, exhibiting its increasing use and potential for growth (Sambo *et al.*, 2019) [2]. Besides yield benefits, HP methods support crop biofortification and improve nutritional quality, meeting consumer demands for safe and healthy produce (Sambo *et al.*, 2019) [2]. These features make HP a considerable option for achieving sustainable growth and productivity in vegetable farming.

Given its many advantages, the existence of traditional HP systems still largely depend on chemical solutions, thus, compromising its stake at environmental impact and overall

sustainability. Development and integration of the concept of organic HP, combining the theory of organic farming with soilless cultivation techniques can serve as alternative pathway to pre-established HP protocols. Nutrients derived from organic sources are utilized as the primary source of nutrition instead of chemical fertilizers, thus, maintaining ecological balance (closed nutrient loops) and reducing synthetic input dependence (Reji *et al.*, 2023) [4]. Organic HP promotes the cultivation of crops with higher quality, meeting consumer demands for environmentally friendly and residue-free products.

In this regard, vermicompost (VC) and its liquid formulation, vermiwash (VW), have attracted much attention as organic nutrient sources for soilless food production systems. VC serves as a slow-release reservoir of both macro-and micronutrients and enhances microbial diversity, which in turn, aids plant growth and substrate health in soilless cultures. Further, VW is a liquid extract obtained from the earthworm-substrate system that is rich in soluble nutrients, plant growth regulators and beneficial microbes. In HP systems, it acts as a bio-enhancer to help root growth, nutrient uptake, and overall vigour of plants which reduces reliance on synthetic nutrient salts. The development of a vermiponic (VP) systems, i.e., combining vermitechnology with HP, offers a more sustainable approach to nutrient management, balancing strict nutrient measurement of HP with ecological benefits from organic amendments.

Experimental evidence has confirmed the viability of VW for use in VP. The VW prepared from livestock biowaste was shown to promote vegetative development and biochemical characteristics of crops compared to traditional aquaponic nutrient solutions (Deepthi *et al.*, 2021) [5]. However, majority of the studies conducted within the domain deal with short-cycle leafy vegetable crops such as amaranthus and lettuce, where an instant response to nutrient solutions is easily measurable. Furthermore, there has been no investigation into VW-based systems in solanaceous crops despite their economic and nutritional value. To cover this gap, chilli (*Capsicum annuum* L.) can serve as a relevant test crop for evaluating the applicability of VP beyond leafy vegetables, thereby broadening the prospects of soilless cultivation from a sustainability context.

The integration of HP with organic nutrient sources like VC and VW underscores the opportunity to create more sustainable and resilient agricultural systems. By minimizing dependence on synthetic fertilizers while ensuring effective nutrient delivery, VP offers a route to environmentally friendly and resource-efficient food production. In this context, the current study assesses the impact of VW-based nutrient solutions on plant growth in VP settings, focusing specifically on growth parameters of chilli as measures of system performance.

Materials and Methods

Experimental site and design

The experiment was conducted at Regional Agricultural Research Station, Kumarakom, Kottayam, Kerala, during January to September 2025. The study was laid out in a completely randomized design (CRD) with 13 treatments and 3 replications. Treatments consisted of VW-based nutrient solutions supplied at two concentrations (5% and 10%), along with control (water) for comparison.

Treatment details

The details of the treatments are presented below:

T_1: VC + 5% concentration (conc.) of VW
T_2: VC + 10% conc. of VW
T_3: VC+ FYM (1:1) + 5% conc. of VW
T_4: VC+ FYM (1:1) +10% conc. of VW
T_5: VC+ FYM+ Cocopeat (2:1:1) + 5% conc. of VW
T_6: VC+ FYM+ Cocopeat (2:1:1) + 10% conc. of VW
T_7: VC+ FYM+ Rice husk ash (2:1:1) + 5% conc. of VW
T_8: VC+ FYM+ Rice husk ash (2:1:1) + 10% conc. of VW
T_9: VC+FYM+ Cocopeat+ Rice husk ash (2:1:1:1) + 5% conc. of VW
T_{10}: VC+FYM+ Cocopeat+ Rice husk ash (2:1:1:1) +10% conc. of VW
T_{11}: Cocopeat + 5% conc. of VW
T_{12}: Cocopeat + 10% conc. of VW
T_13: Cocopeat + normal water (Control)

VW at 5% and 10% concentrations were replaced every week with new solutions to maintain nutrient availability.

Planting material and growing system

Seeds of chilli (*Capsicum annuum* L.,), variety Ujwala, were sown in trays and maintained under nursery conditions. Uniform seedlings, three weeks old, were transplanted into net pots containing 200 g of growing medium and placed in a non-circulating VP system. The net pots were suspended over containers filled with VW nutrient solutions obtained as per the respective treatments. The containers were filled with VW solutions so that the bottom 1 cm of each net pot was immersed, allowing initial root contact with the nutrient medium.

Characterization of vermiwash

The physicochemical and nutrient properties of the vermiwash utilized in the experiment were assessed before its application. The vermiwash exhibited a nearly neutral pH of 7.23 and an electrical conductivity (EC) of 7.52 dS m^{-1}. It comprised of 0.29% nitrogen (N), 0.054% phosphorus (P), 0.15% potassium (K), and 0.488% sulfur (S). Among the secondary nutrients, calcium (Ca) and magnesium (Mg) were found at concentrations of 0.39% and 0.01674 %, respectively. The levels of micronutrients were recorded as 30.6 mg kg^{-1} Fe, 3.2 mg kg^{-1} Zn, 8.3 mg kg^{-1} Mn, 2.3 mg kg^{-1} Cu, and 4.10 mg kg^{-1} B. The comprehensive nutrient profile is detailed in Table 1.

Table 1: Physicochemical properties of vermiwash

Nutrient	Concentration
N (%)	0.29
P (%)	0.054
K (%)	0.15
S (%)	0.04885
Ca (%)	0.39
Mg (%)	0.01674
Fe (mg kg^{-1})	30.6
Zn (mg kg^{-1})	3.2
Mn (mg kg^{-1})	8.3
Cu (mg kg^{-1})	2.3
B (mg kg^{-1})	4.10
pH	7.23
EC	7.52

Preparation and application of VW

VW was prepared from a vermicomposting unit in which rice straw, banana pseudostem, and cow dung were used as substrates in the ratio of 8:1:2. Prior to vermicomposting, the rice straw was pre-decomposed using the Pusa decomposer developed at Indian Agricultural Research Institute (IARI), New Delhi, to accelerate lignocellulosic breakdown and improve its suitability as feed material. The mixture was further enriched with 2% rock phosphate to enhance phosphorus availability and then inoculated with 500 grams of the epigeic earthworm *Eudrilus eugeniae*. VW was collected using a vermireactor unit as described in the *Package of Practices Recommendations: Crops* (2024, 16th edition) by Kerala Agricultural University. 1 L of water was added to the plastic container consisting of 5 kg of VC and active earthworm populations for VW extraction. The extract was drained after a 24-hour incubation period and stored post filtration. For the experiment, concentrated VW was diluted with water to prepare 5% and 10% working solutions, which were supplied to the VP system and replaced weekly.

Growth parameters recorded

Plant growth was assessed at regular intervals by measuring plant height (cm), number of leaves, number of branches per plant, maximum root length. Phenological observations such as days to first flowering were recorded from the date of transplanting.

Plant height

Plant height was measured from the base of the stem to the tip of the terminal leaf using a centimetre scale.

Number of leaves

Total number of fully expanded leaves per plant was counted and recorded.

Number of branches

The number of primary branches arising from the main stem per plant was recorded.

Root length

Root length was measured from the root-shoot junction to the tip of the longest root using a centimetre scale.

Statistical analysis

The data collected were subjected to statistical analysis using the software GRAPES developed by department of agricultural statistics, Kerala Agricultural University. Treatment means were compared using analysis of variance (ANOVA) and significance was determined at the 5% probability level.

Results

Plant growth parameters at 40 days after transplantation (DAT)

Plant growth characteristics as influenced by vermiponics-based fertilization at 40 day stage and 60 day stage have been presented in Table 2 and Table 3 respectively. Assessment at 40-day stage (post-transplantation) evidenced a significant treatment impact on the plant growth parameters. Height-wise, T_{10} (29.30 cm) exhibited highest readings. Further, T_2, T_6, T_7, and T_8 showed significant growth increase from control treatment, which could only reach 12.97 cm. T_7 emerged as the best treatment in terms of number of leaves (20.67), which was on par with T_2 and T_8. Maximum root length varied significantly across treatments with T_{12} producing the longest roots (25.17 cm) which was statistically on par with T_9 (23.67 cm) and T_2 (23.50 cm), while the shortest was recorded in T_1 (10.03 cm). Overall, results at 40 DAT stage suggest that various treatments significantly boosted vegetative growth and root length compared to the control, although the best treatment for respective parameter differed.

Table 2: Growth parameters at 40 DAT stage.

Treatments	Plant height (cm)	Number of leaves per plant	Maximum root length (cm)	Number of branches per plant
T_1	24.00^{abc}	17.66^{abc}	10.03^{d}	0.333^{ns}
T_2	27.26^{a}	19.33^{ab}	23.50^{ab}	0.667^{ns}
T_3	23.36^{abc}	16.00^{abcd}	15.03^{bcd}	0.667^{ns}
T_4	25.83^{ab}	17.66^{abc}	14.76^{bcd}	0.667^{ns}
T_5	20.73^{bcd}	12.00^{bcde}	12.43^{cd}	0.333^{ns}
T_6	27.63^{a}	17.66^{abc}	13.80^{cd}	0.333^{ns}
T_7	27.63^{a}	20.66^{a}	15.86^{bcd}	0.333^{ns}
T_8	27.73^{a}	19.33^{ab}	16.93^{abcd}	0.667^{ns}
T_9	25.73^{ab}	13.33^{abcde}	23.66^{ab}	0.333^{ns}
T_{10}	29.30^{a}	16.66^{abcd}	21.40^{abc}	0.667^{ns}
T_{11}	18.90^{cde}	9.00^{de}	17.73^{abcd}	0.333^{ns}
T_{12}	14.83^{de}	10.00^{cde}	25.16^{a}	0.000^{ns}
Control	12.96^{e}	6.00^{e}	13.10^{cd}	0.000^{ns}
CD	5.97	7.715	9.301	NS
SE(m)	2.054	2.654	3.199	0.413

*CD: Critical difference. SE (m): Standard error of mean (3 replicates). Treatments with same letters are not significantly different at $p<0.05$ by one way ANOVA, followed by Least Significance Difference test, respectively. NS = non-significant at $p>0.05$.

Plant growth parameters at 60 DAT stage

Significant variations in treatments were observed in terms of growth parameters at 60 DAT stage. The highest plant height was recorded by T_8 (48.73 cm), followed by T_{10} and T_7, whereas the lowest height was observed in the control. Leaf frequency was highest in T_1 (86.33), which was closely on par with T_4. Longest Root length was reported in T_6 and shortest in T_{11}. Branching frequency was highest in T_1 (7.33) which was statistically on par with T_8, whereas primary branching was not observed in T_{12} and control. Hence, T_1, T_4, T_7, and T_8 outperformed other treatments on

most parameters, while T_{11}, T_{12}, and control presented the least active growth responses.

Number of days to first flowering

The days to first flowering varied significantly across treatments. The earliest bloom occurred in T_8 (40.00 days), which was statistically at par with T_7 (42.00 days). Statistically, the longest days to flowering was exhibited by T_{11} (70.00 days). Notably, control plants did not flower during the observation period, indicating complete inhibition of reproductive transition in water.

Table 3: Growth parameters at 60 DAT stage

Treatment	Plant height (cm)	Number of leaves per plant	Root length (cm)	Number of branches per plant	Number of days to first flowering
T_1	44.83^{abc}	86.33^{a}	21.16^{ab}	7.33^{a}	45.00^{cd}
T_2	38.73^{bc}	64.66^{abc}	14.83^{bcd}	4.66^{b}	48.00^{c}
T_3	43.33^{abc}	55.33^{bcd}	12.13^{bcd}	4.33^{b}	45.00^{cde}
T_4	44.70^{abc}	74.66^{ab}	28.16^{a}	5.00^{b}	42.00^{cde}
T_5	37.03^{c}	38.66^{defg}	8.56^{cd}	3.33^{bcd}	44.66^{cde}
T_6	40.03^{abc}	48.66^{cde}	30.16^{a}	4.00^{bc}	46.66^{cd}
T_7	47.83^{ab}	65.66^{abc}	29.50^{a}	5.00^{b}	42.00^{de}
T_8	48.73^{a}	68.00^{abc}	17.00^{bc}	5.33^{ab}	40.00^{e}
T_9	39.06^{abc}	46.00^{cdef}	12.16^{bcd}	3.33^{bcd}	56.00^{b}
T_{10}	48.60^{a}	29.33^{efgh}	9.50^{cd}	2.00^{cde}	61.00^{b}
T_{11}	24.63^{d}	18.50^{fgh}	5.85^{d}	1.00^{de}	70.00^{a}
T_{12}	24.63^{d}	17.33^{gh}	16.66^{bcd}	0.00^{e}	-
Control	18.25^{d}	9.50^{h}	8.45^{cd}	0.00^{e}	-
CD	9.67	24.65	9.69	2.28	4.93
SE(m)	3.313	8.442	3.322	0.782	1.635

*CD: Critical difference. SE(m): Standard error of mean (3 replicates). Treatments with same letters are not significantly different at $p < 0.05$ by one way ANOVA, followed by Least Significance Difference test, respectively.

Discussion

Application of VW at 5% and 10% in an outdoor VP setup significantly affected growth and development of chilli (*Capsicum annuum* L.). Parametric differentiation included: increase in plant height, leaf number, highest root length, and branching and decrease in time duration for flowering. These results point to VW acting both as a nutrient source and a biostimulant. VW contains plant growth regulators—auxins, cytokinins, and gibberellins—plus soluble nutrients, humic substances, and beneficial microbes that together enhance plant performance (Tahaseen, 2025) [10].

Between the two concentrations, plants given 10% VW consistently outperformed those given 5%. The greater increases in height and leaf number with 10% VW likely stem from better availability of soluble nitrogen and growth-promoting compounds that drive cell elongation and division. Root growth was also superior at the higher concentration, suggesting VW supports rhizogenesis by improving nutrient uptake efficiency and root mass. These findings agree with Akazawa *et al.* (2023) [6], who reported that tomato plants treated with earthworm-derived VW showed longer shoots, larger leaf area, and bigger fruits at higher VW levels, without signs of growth suppression.

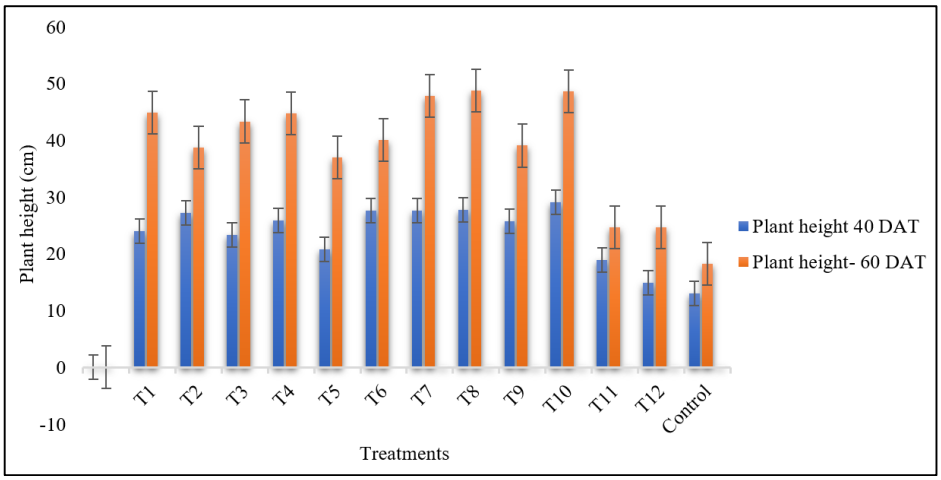

Fig 1: Plant height of chilli at 40 and 60 days after transplantation (DAT) under different treatments.

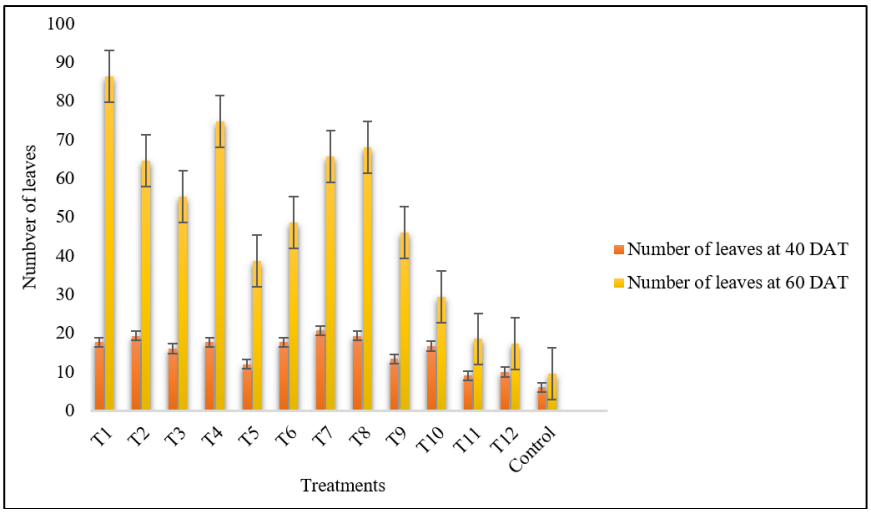

Fig 2: Number of leaves of chilli at 40 and 60 days after transplantation (DAT) under different treatments.

The stimulatory effect on vegetative growth seen in this study is supported by Padmanaban (2022) [9], who found that foliar application of VW from *Eudrilus eugeniae* significantly increased shoot length, leaf length, and leaf count in chilli. This suggests that VW's biochemical richness, especially its phytohormones, directly promotes vegetative growth in capsicum. The earlier flowering observed with the 10% VW treatment further highlights its role in boosting vegetative vigour and speeding the transition to reproductive growth. Khan, Uddin, and Sahoo (2014) [8] reported a similar effect, wherein, foliar VW combined with AMF inoculation improved nutrient uptake efficiency and reduced flowering time in *Capsicum assamicum* (Bhut Jolokia).

Beyond chilli, VW has shown benefits in many other crops, supporting these findings. Awadhpersad, and Ansari (2021) [7] reported notable improvements in tomato growth and yield when VW and VC were used, attributing the gains to better nutrient uptake and increased microbial activity. Likewise, Akazawa *et al.* (2023) [6] noted that VW acts not just as a nutrient source but as a plant biostimulant, improving both morphological development and reproductive performance. Together, these studies show that VW, whether applied as a foliar spray or used in HP/VP systems boosts plant productivity by supplying diverse bioactive compounds and beneficial microbes.

Overall, these results support earlier studies and expand the use of VW in outdoor VP for growing chillies. The consistent strong performance of 10% VW across growth measures, i.e., height, leaf number, branching, root length, and flowering time indicates that higher concentrations within the optimal range provide more readily available nutrients and growth-promoting substances. This points to VW as a promising, sustainable resource for chilli production in soilless and organic systems, where managing nutrient supply and growth is key to success.

Conclusion

The results show that nutrient solutions made from VW significantly improve growth and development of chilli plants in a non-circulating VP system. Using VW at 5% and 10% boosted plant height, leaf count, root length, branching, and time to first flowering, with the 10% dose generally outperforming 5%. The rapid vegetative growth and earlier flowering seen with VW match its role as a biostimulant, supplying soluble macro-and micronutrients, plant growth regulators, and beneficial microbes that together improve nutrient uptake, cell expansion, and root development. Using VW as a nutrient solution with organic substrates improves yield and quality while helping establish sustainable, resource-efficient, residue-free vegetable production. Therefore, this research highlights VW-driven VP as a practical, scalable approach for sustainable farming that can help meet growing food demand while cutting ecological harm.

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