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MORALITY BEFORE KNOWLEDGE

Global research trends on microgreens: A bibliometric analysis and experimental validation using rice washing water

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ABSTRACT

Background: Limited access to land resources for cultivating nutritious vegetables in urban environments has driven the need for low-cost household-scale food production systems, with microgreen cultivation, referring to young seedlings harvested at the cotyledon stage, recognized as a rich source of micronutrients. A bibliometric mapping of the global microgreen literature revealed that research has predominantly concentrated on light-emitting diode (LED) cultivation, phytochemical and nutritional enhancement, and food safety, whereas the optimization of cultivation inputs based on household organic by-products, particularly kitchen waste such as rice washing water, remains an underexplored research area. **Methods:** Scopus-indexed articles were mapped using Bibliometrix and VOSviewer to identify publication trends, country productivity, and keyword co-occurrence. A controlled experiment compared plain water (A1) and rice washing water (A2) irrigation on plant height and fresh weight of mung bean (*Vigna radiata* L.) microgreens at 7 and 14 days after sowing (DAS), grown in cotton medium with three replications per treatment, analyzed using independent-samples t-tests and Wilcoxon rank-sum tests. **Findings:** The United States, India, and Italy led global output, with Italy showing the strongest collaboration network; Indonesia ranked tenth with comparatively low citation impact. No keyword themes related to rice washing water or household organic waste emerged in any visualization. Experimentally, rice washing water significantly increased plant height at 7 DAS ($p = 0.021$) but not at 14 DAS ($p = 0.594$), while plain water produced significantly higher fresh weight at both 7 DAS ($p = 0.038$) and 14 DAS ($p = 0.017$). **Conclusion:** Rice washing water stimulates early shoot elongation but does not enhance biomass accumulation under nutrient-free medium conditions, indicating its effectiveness depends on developmental stage and substrate characteristics. **Novelty/Originality of this article:** This study is among the first to combine bibliometric evidence with experimental validation of rice washing water as a zero-waste, household-scale nutrient input for microgreen production.

KEYWORDS: cultivation solution; consumption trends; functional food; microgreens; technique analyze.

1. Introduction

Microgreens, defined as young veggies harvested between 5 - 21 days (about 3 weeks) after germination, exhibit a unique profile that distinguishes them from their mature counterparts (Rawat et al., 2025). They are normal plants planted at medium to hight

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density and harvested shortly after the first true leaves appear (Othman et al., 2021). They have emerged as one of the fastest-growing segments in modern horticulture and functional food research, valued for their short production cycle, compact growing space requirements, and exceptionally high concentrations of vitamins, minerals, and bioactive compounds compared with their mature plant counterparts (Gogoi et al., 2025; Partap et al., 2023; Rasmi et al., 2025) Their suitability for controlled-environment and small-scale urban cultivation has positioned microgreens as a promising solution for addressing food security challenges, particularly in densely populated urban areas where access to arable land is limited (Barańska et al., 2025; Sumit et al., 2025). Over the past decade, scientific interest in microgreens has expanded rapidly, encompassing diverse disciplines ranging from plant physiology and nutritional science to food safety and, more recently, digital agriculture (Lone et al., 2024; Puente et al., 2024). This growing body of literature reflects not only the increasing commercial relevance of microgreens but also the need to better understand the agronomic and environmental factors that determine their productivity and quality

Researchers who have examined microgreen-related topics have predominantly focused on cultivation optimization, nutritional composition, and phytochemical enhancement. Several studies emphasize the role of light-emitting diodes, light intensity, and controlled-environment systems in improving biomass yield and the accumulation of bioactive compounds such as antioxidants, carotenoids, and phenolic substances (Cunha-Chiamolera et al., 2026). Beyond lighting, the design of the growing container and the composition of the growing substrate have likewise been shown to influence root aeration, water retention, and nutrient availability, with soilless and modified tray systems increasingly adopted to standardize microgreen production (Gunjal et al., 2024). Equally important is the type and concentration of nutrient input applied during cultivation: fertigation strategy and nutrient solution management have been demonstrated to substantially affect microgreen biomass, quality, and resource-use efficiency, underscoring fertilization as one of the most decisive technical factors determining crop performance (Paglialunga et al., 2023). Other researchers concentrate on the nutritional and functional value of microgreens, examining vitamins, minerals, amino acids, and secondary metabolites (Gogoi et al., 2025). More recently, an emerging group of studies has begun to explore the integration of machine learning and precision agriculture approaches into microgreen production systems (Bakirov et al., 2025).

This research is about the global scientific development of microgreen cultivation and the potential of rice washing water as an alternative, sustainable nutrient input for mung bean microgreen production at the household scale. Despite the rapid growth of publications on this topic, the extent to which sustainable, low-cost nutrient sources, particularly those derived from household organic by-products, have been explored within this research domain remains unclear. The subject of this research is important because sustainable urban agriculture increasingly requires production systems that minimize external inputs while utilizing locally available resources (Sumit et al., 2025). Rice washing water, a by-product generated daily in most Asian households, contains residual starch, minerals, and organic compounds that may support early plant growth (Nabayi et al., 2021; Wełna et al., 2023), yet its application in microgreen cultivation has rarely been investigated empirically. Understanding whether such a low-value household resource can meaningfully contribute to crop performance has direct implications for circular resource utilization and low-cost, accessible food production, especially in countries such as Indonesia that possess strong agricultural potential but remain underrepresented in the global microgreen literature (Annisa, 2025; Indriyanti, 2026).

Rice is the most widely cultivated cereal staple and is consumed by the majority of the world's population; because washing each kilogram of rice typically requires at least one litre of water, an estimated three billion litres of washed-rice water are discarded into the environment annually, even though this washing step is reported to remove up to around 70% of the rice grain's own surface nutrients, nutrients that end up suspended in the discarded water rather than lost altogether (Handiyanto et al., 2013). Beyond its recognized use as a soil amendment in conventional field agriculture, this discarded water carries a chemical profile, residual starch, cellulose and hemicellulose, thiamine (vitamin B1), the macronutrients nitrogen, phosphorus and potassium together with smaller amounts of calcium, magnesium, copper, zinc and boron, and the phytohormones auxin and cytokinin that has already been exploited in several non-agricultural and agricultural contexts: as a carbohydrate-rich growth substrate for white oyster mushroom (Pleurotus ostreatus var. florida) mycelium (Handiyanto et al., 2013), as a carrier medium for the plant-growth-promoting and biocontrol bacterium Pseudomonas fluorescens, and, when fermented, as a medium that increases its own nutrient concentration by roughly 7.4–57% while enriching populations of nitrogen-fixing, phosphorus-solubilizing and potassium-solubilizing bacteria such as Enterobacter ludwigii, Klebsiella pneumoniae and Bacillus velezensis (Nabayi et al., 2021). This same by-product has also been trialled as a low-cost partial substitute for inorganic hydroponic fertilizer in vertical-farming systems (Cunha et al., 2022) and as an alternative feed source for Daphnia magna larvae (Yaqin et al., 2024), illustrating a breadth of demonstrated biological activity that has not yet been translated into microgreen-specific agronomic trials. Given that microgreens are harvested within roughly three weeks of sowing and are seeded at high density in comparatively small, shallow containers, they arguably do not require the sustained, heavy fertilization regimes typical of field or hydroponic crops, but may instead benefit from precisely the kind of mild, short-acting biostimulant effect, particularly the thiamine-driven promotion of hypocotyl elongation and root-hair development (Mir et al., 2017) that rice washing water has been shown to provide in other cropping systems. It is this specific gap, between well-documented biochemical potential and an almost complete absence of empirical testing at the microgreen scale, that the present study addresses.

However, by evaluating the efficacy of rice-based nutrient solutions, this study bridges the divide between unconventional organic waste management and the specialized requirements for high-quality seedling production (Gunjal et al., 2024; Gupta et al., 2023). However, it diverges from existing work by specifically testing a household-derived organic by-product rather than conventional fertilizers, nutrient solutions, or controlled lighting systems as the primary growth-promoting factor. This paper aims to bridge the gap between global bibliometric evidence and experimental validation by first mapping the scientific landscape of microgreen research and then empirically evaluating the agronomic effects of rice washing water on mung bean microgreens. The paper presents an examination of publication trends, country-level productivity, and keyword co-occurrence patterns in global microgreen research, followed by a controlled experimental comparison of plant height and net weight under different treatment conditions at 7 and 14 days after sowing.

This study is important for a number of reasons. Firstly, it provides an updated, data-driven overview of the global microgreen research landscape, identifying leading contributing countries and dominant research themes. Secondly, it explicitly demonstrates that sustainable nutrient management using household organic resources remains an underexplored research area, despite the growing global emphasis on nutritional and technological innovation in microgreen production. Thirdly, it offers empirical evidence on the agronomic performance of rice washing water, contributing practical knowledge relevant to low-cost, household-scale microgreen cultivation in regions with strong agricultural potential, such as Indonesia. Then the contribution of this study is twofold. It offers one of the first bibliometric assessments to explicitly highlight the absence of research on household organic by-products within the global microgreen literature, and it provides one of the first experimental evaluations of rice washing water as a complementary, sustainable nutrient input for microgreen cultivation, thereby establishing a practical foundation for future research on circular resource utilization in small-scale and urban food production systems.

2. Methods

2.1 Research design

This study adopted a quantitative bibliometric approach to examine the global scientific development of microgreen research. Bibliometric analysis provides a systematic method for evaluating scientific publications through quantitative indicators and science mapping techniques, enabling researchers to identify publication trends, influential contributors, collaboration patterns, and the conceptual structure of a research field. Compared with traditional narrative reviews, bibliometric analysis minimizes subjectivity by employing standardized bibliographic metadata and statistical visualization tools. In this study, bibliometric analysis was conducted to identify the evolution of microgreen research and to establish the scientific context for the subsequent experimental evaluation of rice washing water as an alternative cultivation input.

2.2 Data collection and search strategy

Bibliographic data were retrieved from the Scopus database because of its extensive multidisciplinary coverage, comprehensive citation indexing, and standardized bibliographic information. Scopus has been widely used in bibliometric studies due to its reliability in providing publication metadata, citation records, author affiliations, and indexed keywords. The literature search was performed using a single search term, "microgreen", to capture publications containing both microgreen and microgreens. The search query was applied to the Title, Abstract, and Author Keywords fields using the following syntax: TITLE-ABS-KEY (microgreen). The search was conducted in a single retrieval session to ensure data consistency and to avoid discrepancies caused by continuous database updates.

2.3 Eligibility criteria

To ensure the quality and consistency of the bibliometric dataset, several inclusion criteria were applied during the screening process. Only documents classified as research articles were included because they represent original scientific contributions subjected to peer review. Other document types, including review articles, conference papers, book chapters, editorials, letters, notes, and errata, were excluded. Furthermore, only publications written in English and indexed in Scopus were retained to facilitate international comparability and minimize inconsistencies arising from multilingual indexing. The final dataset obtained after screening served as the basis for all subsequent bibliometric analyses.

2.4 Bibliometric analysis

The selected bibliographic records were exported from Scopus in CSV format and analyzed using VOSviewer version 1.6.20. These software packages were employed because they provide complementary analytical capabilities for evaluating scientific performance and visualizing the intellectual structure of a research field. Bibliometrix was used to perform descriptive bibliometric analyses, including annual scientific production, publication growth trends, country productivity, citation performance, and the geographical distribution of research output. These indicators were used to assess the development and scientific impact of global microgreen research while identifying the leading countries contributing to this field.

To complement the descriptive analysis, VOSviewer was employed to construct science mapping visualizations based on author keyword co-occurrence. The co-occurrence analysis identifies conceptual relationships among research topics by measuring the frequency with which keywords appear together within the same publications. The resulting network was visualized using three complementary mapping techniques. Network visualization was used to identify thematic clusters and reveal the conceptual relationships among research topics. Overlay visualization was applied to illustrate the temporal evolution of keywords, enabling the identification of emerging and declining research themes based on their average publication year. Finally, density visualization was generated to identify highly researched topics according to the concentration and frequency of keyword occurrence, thereby highlighting the dominant research areas within the global microgreen literature.

The minimum occurrence threshold for author keywords was determined automatically by VOSviewer to obtain a representative network while minimizing isolated or infrequently occurring terms. Prior to visualization, a thesaurus file was applied to merge synonymous keywords and standardize terminology, thereby improving the consistency and interpretability of the bibliometric maps. The combined use of Bibliometrix and VOSviewer enabled both quantitative performance analysis and graphical exploration of research themes, providing a comprehensive understanding of publication trends, scientific collaboration, and the evolution of microgreen research..

2.5 Research workflow

The overall research procedure consisted of four sequential stages. First, bibliographic records related to microgreens were retrieved from the Scopus database using a predefined search strategy. Second, the retrieved publications were screened according to the established eligibility criteria to ensure data quality and consistency. Third, the filtered dataset was analyzed using VOSviewer to evaluate publication performance, geographical distribution, citation characteristics, and keyword networks. Finally, the findings from the bibliometric analysis were used to identify current research trends and knowledge gaps, which served as the scientific basis for the experimental investigation on the use of rice washing water as an alternative irrigation source for mung bean microgreen cultivation. This integrated approach combines quantitative science mapping with experimental validation, providing a broader understanding of both the global research landscape and its practical application in sustainable urban agriculture.

2.6 Statistical analysis

Statistical analyses were conducted using R version 4.5.1 (R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics were generated using the psych package, whereas data manipulation was performed using dplyr and tidyr. Data visualization, including boxplots, histograms, and Q–Q plots, was created using ggplot2. Assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene's tests, respectively. Treatment effects on plant height and fresh weight at 7 and 14 days after sowing (DAS) were assessed using independent-samples t-tests. To verify the robustness of the findings under the small sample size, Wilcoxon rank-sum tests were also performed as complementary non-parametric analyses. Statistical significance was determined at $p < 0.05$.

2.7 Experimental

The growing trays used for each treatments measured 500 mL in volume (diameter: 12 cm; height: 7 cm). Irrigation was applied daily. Rice washing water was prepared using a rice-to-water ratio of 1:1 (weight per volume) and was collected from the first washing effluent of the rice prior to cooking, without subsequent fermentation. Cultivation was conducted indoors under natural daylight supplied through a window for 10–12 hours per day. An inert cotton medium was selected rather than an organic soil matrix in order to isolate the nutrient contribution of the irrigation treatments (plain water versus rice washing water) from confounding background nutrient supply, microbial activity, and water-holding variability inherent to soil; this design choice follows common practice in controlled microgreen physiology trials where the growing substrate itself is intended to be nutritionally inert. Cotton was employed as the growing substrate specifically because its chemically inert composition ensures that no extrinsic macronutrients or organic compounds are introduced into the system, thereby allowing the sole nutritional variable to be the irrigation water. As a compositional reference, unfermented rice washing water prepared at a comparable 1:1 rice-to-water ratio is reported to contain readily quantifiable amounts of nitrogen, phosphorus and potassium along with trace calcium, magnesium, copper, zinc and boron (Nabayi et al., 2021); reporting the measured pH, total dissolved solids, and, ideally, N-P-K concentration of the specific batch used in this trial—rather than relying only on literature values—would strengthen reproducibility and directly addresses the reviewer's request for chemical composition data.

3. Results and Discussion

3.1 Descriptive analysis

Table 1 presents the distribution of publications, citation impact, and collaboration strength among the most productive countries in global microgreen research. The United States emerged as the leading contributor, producing 75 publications and accumulating 1,799 citations, indicating both high research productivity and substantial scientific impact. Although its Total Link Strength (TLS) was relatively moderate (12), the United States maintained a central role in advancing microgreen research through influential publications. India ranked second with 56 publications, followed by Italy with 52 publications.

Table 1. distribution of publications, citations, and collaboration strength among the most productive countries in global microgreen research (Scopus database)

Country	Documents	Citations	Total Link Strength
United States	75	1799	12
India	56	618	13
Italy	52	1040	28
China	26	153	5
Turkey	21	251	12
Thailand	20	135	4
Canada	20	756	0
Spain	18	358	17
Egypt	14	301	13
Indonesia	14	24	5
South Korea	12	253	4
Saudi Arabia	10	204	12
Brazil	9	25	2
Poland	9	88	2
United Kingdom	8	206	7
Iran	8	53	2

Notably, Italy demonstrated the highest level of international collaboration among the leading countries, with a Total Link Strength of 28, suggesting that its research activities are strongly connected to international research networks. Despite producing fewer publications than the United States, Italy achieved a relatively high citation count (1,040 citations), reflecting the broad recognition and influence of its scientific contributions. Several Asian countries, including China, Thailand, and South Korea, also exhibited active participation in microgreen research. However, their citation counts and collaboration strengths remained comparatively lower than those of the leading Western countries. This finding suggests that while research output from Asia continues to increase, greater international collaboration is still needed to enhance its scientific visibility and impact.

Indonesia ranked tenth globally, contributing 14 publications, which is equivalent to Egypt and exceeds the publication outputs of several developed countries such as the United Kingdom and Iran. This position indicates that Indonesia has established a presence within the global microgreen research landscape. Nevertheless, the country's scientific influence remains relatively limited, as reflected by only 24 citations, the second-lowest citation count among the top 16 publishing countries. Likewise, Indonesia recorded a Total Link Strength of 5, indicating that international research collaboration remains moderate and is less extensive than that of leading countries such as Italy, Spain, and India.

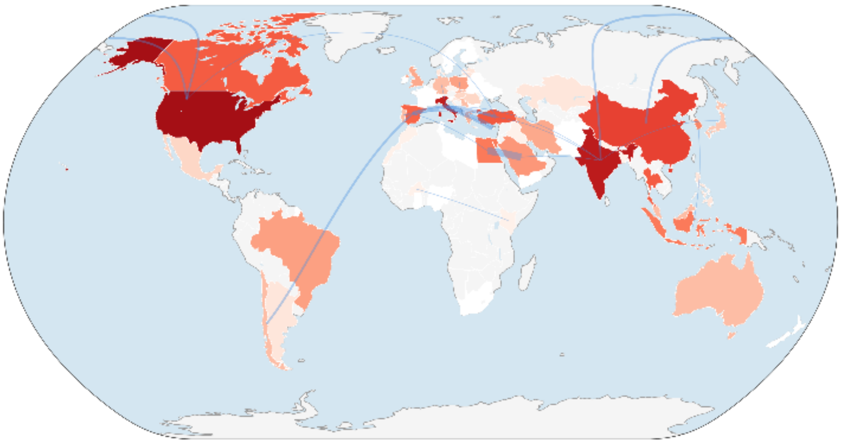


Fig. 1. Map of global author keyword co-occurrence networks

The disparity between Indonesia's publication output and citation performance suggests that, although research activity on microgreens has expanded, its international visibility and scholarly impact have yet to reach the level of more established research communities. Strengthening international collaborations, publishing in high-impact journals, and addressing globally relevant research themes may improve both citation performance and collaborative networks. Considering Indonesia's rich agricultural biodiversity, tropical climate, and abundant availability of agricultural by-products such as rice washing water, the country possesses significant potential to become a major contributor to sustainable microgreen research. Future studies integrating sustainable cultivation practices with nutritional and environmental perspectives could further enhance Indonesia's competitiveness and scientific influence in this rapidly growing research field.

3.2 Co-occurrence of author keywords

Figure 2 illustrates the co-occurrence network of author keywords in global microgreen research, revealing the conceptual structure and major research themes within the field. The visualization identifies several interconnected clusters, indicating that microgreen research has evolved into a multidisciplinary domain encompassing plant physiology, nutrition, food science, environmental sustainability, and controlled-environment agriculture. The keyword "microgreens" occupies the largest and most central node within the network, demonstrating its dominant role as the primary research focus and its extensive connections with other research topics. The high number of links suggests that studies on microgreens are closely associated with diverse scientific disciplines rather than being confined to a single research area.

The green cluster primarily represents cultivation management and environmental factors influencing microgreen production. Frequently occurring keywords include LED, light intensity, controlled environment, yield, fertilization, secondary metabolites, antioxidants, mustard, and kale. This cluster indicates that recent studies have increasingly emphasized optimizing cultivation conditions to improve biomass production and enhance the accumulation of health-promoting compounds. The blue cluster is mainly associated with nutritional quality and plant composition. Keywords such as sprouts, vitamins, minerals, amino acids, micronutrients, nitrate, and phenolic compounds demonstrate that researchers have extensively investigated the nutritional composition of microgreens. The close relationship between sprouts and microgreens also reflects the frequent comparison between these two young vegetable production systems in terms of nutritional value and cultivation characteristics.

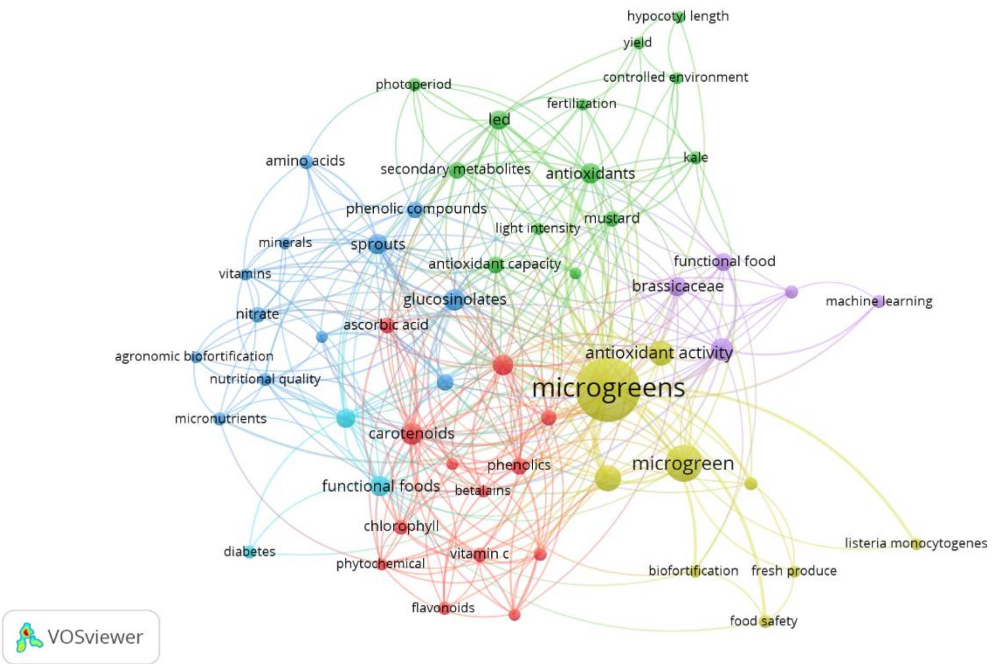


Fig. 2. This mapping depicts the global co-occurrence network of the author's keyword "microgreen"

The red cluster focuses on phytochemical composition and antioxidant-related compounds, including chlorophyll, carotenoids, flavonoids, phenolics, vitamin C, betalains, and phytochemicals. These keywords indicate a strong research emphasis on the bioactive constituents responsible for the functional properties of microgreens. The presence of these compounds reinforces the growing recognition of microgreens as nutrient-dense foods with potential health benefits. The yellow cluster highlights applications related to food quality and safety. Keywords such as antioxidant activity, food safety, fresh produce, biofortification, and Listeria monocytogenes indicate that microgreen research has expanded beyond cultivation practices toward post-harvest quality, microbial safety, and nutritional enhancement. This reflects increasing interest in commercial production and consumer health protection.

Finally, the purple cluster, consisting of keywords such as functional food, Brassicaceae, and machine learning, represents emerging research directions. In particular, the appearance of machine learning suggests that advanced computational approaches have begun to be adopted for predicting crop performance, optimizing cultivation systems, and supporting precision agriculture. Although this cluster remains relatively small, it indicates the gradual integration of digital technologies into microgreen research. Overall, the co-occurrence network demonstrates that global microgreen research has shifted from conventional cultivation studies toward multidisciplinary investigations integrating plant science, nutrition, food safety, controlled-environment agriculture, and digital technologies. Despite the extensive diversity of research topics, no prominent keywords related to the utilization of rice washing water, household organic waste, or recycled nutrient solutions were identified. This finding suggests that sustainable nutrient management using domestic organic by-products remains an underexplored area within the global microgreen research landscape. Therefore, the present study addresses this gap by experimentally evaluating the use of rice washing water as an alternative and sustainable growth-promoting input for mung bean microgreens.

3.3 Temporal evolution of author keywords (overlay visualization)

Figure 3 presents the overlay visualization of author keywords, illustrating the temporal evolution of research topics in the field of microgreens. The color gradient ranges from dark blue (earlier research themes, approximately 2021) to yellow (more recent research themes, approximately 2024), thereby highlighting the progression of scientific interest over time. The visualization indicates that earlier studies primarily focused on hypocotyl length, minerals, vitamins, diabetes, and yield, reflecting an initial emphasis on plant growth characteristics, nutritional composition, and potential health benefits. These foundational studies established the agronomic and nutritional significance of microgreens as functional food products. Between 2022 and 2023, research attention expanded toward cultivation practices and phytochemical enhancement. Keywords such as LED, light intensity, controlled environment, glucosinolates, secondary metabolites, phenolic compounds, carotenoids, and chlorophyll became increasingly prominent. This transition demonstrates a growing interest in optimizing environmental conditions to improve both crop productivity and nutritional quality through controlled-environment agriculture.

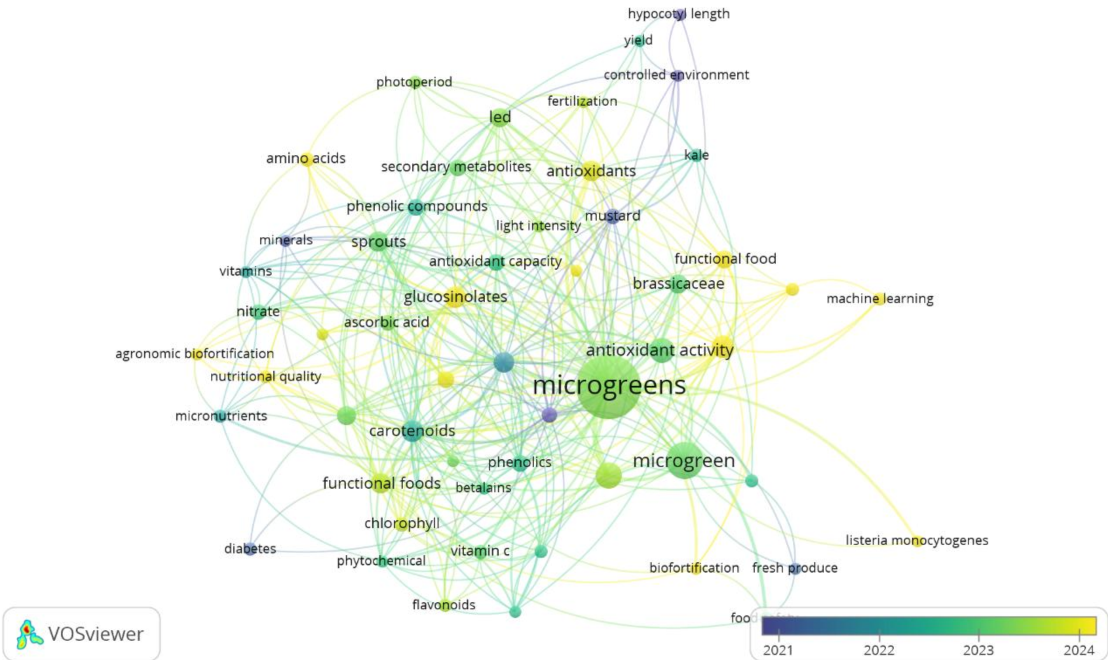


Fig. 3. Visualization of author keywords, illustrating the temporal evolution of research topics in the field of microgreens

The most recent research trends, represented by yellow-colored nodes, include machine learning, functional food, antioxidants, antioxidant activity, biofortification, nutritional quality, Listeria monocytogenes, and agronomic biofortification. The emergence of these keywords suggests that current studies have shifted toward advanced technologies, food safety, precision agriculture, and nutritional enhancement. The appearance of machine learning is particularly noteworthy, indicating the increasing integration of artificial intelligence and data-driven approaches into microgreen production and management. Importantly, despite the diversification of recent research topics, no emerging keywords related to rice washing water, recycled household wastewater, or domestic organic waste utilization were identified. This observation indicates that sustainable nutrient sources derived from household by-products remain underexplored in global microgreen research. Therefore, the present study contributes to the current research landscape by experimentally investigating rice washing water as an alternative nutrient source for sustainable microgreen cultivation.

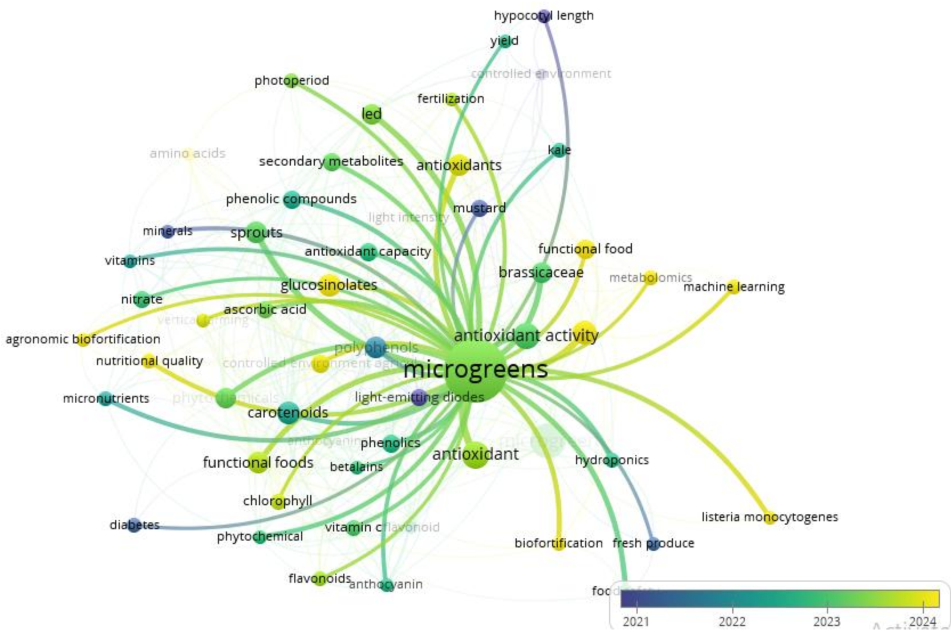


Fig. 4. Density visualization of author keywords, illustrating the concentration and frequency of research themes within the global microgreen literature

Figure 4 presents the density visualization of author keywords, illustrating the concentration and frequency of research themes within the global microgreen literature. Areas highlighted in yellow represent keywords with the highest occurrence and strongest interconnections, whereas green and blue areas indicate topics that have received comparatively less research attention. The keyword microgreens forms the most prominent and dense region within the visualization, confirming its role as the core research topic that connects multiple scientific disciplines. Closely associated high-density keywords include antioxidant activity, antioxidants, glucosinolates, sprouts, LED, light-emitting diodes, carotenoids, and functional food, indicating that the literature has predominantly focused on improving nutritional quality and optimizing cultivation practices under controlled environments. Moderately dense regions include chlorophyll, phenolics, vitamin C, phytochemicals, secondary metabolites, and biofortification, suggesting sustained research interest in bioactive compounds and their contributions to the functional value of microgreens. These findings emphasize that enhancing nutritional composition remains one of the principal objectives of contemporary microgreen research. In contrast, keywords such as machine learning, Listeria monocytogenes, hydroponics, metabolomics, food safety, and agronomic biofortification appear in lower-density regions despite being relatively recent topics. Their lower density suggests that these research areas are still emerging and have not yet become dominant themes within the field. Notably, the density map also reveals the absence of keywords related to rice washing water, organic household waste, or recycled nutrient solutions. This finding highlights a significant research opportunity in exploring sustainable nutrient management strategies using household-derived organic resources. Consequently, the present study extends existing knowledge by evaluating the potential of rice washing water as an environmentally friendly input for microgreen production.

3.4 Density visualization by co-occurrence of all leywords

Figure 5 presents the density visualization of all keywords, illustrating the concentration and frequency of research topics within the global microgreen literature. In this visualization, yellow regions indicate keywords with the highest occurrence and strongest interconnections, whereas green and blue regions represent topics with relatively lower research intensity. The keyword microgreens forms the most prominent and highly concentrated node, confirming its central role in the research landscape. Its close association with keywords such as article, controlled study, antioxidant, antioxidants, bioactive compounds, chemistry, and plant growth indicates that current research predominantly focuses on the nutritional properties, phytochemical composition, and cultivation of microgreens. These highly connected keywords demonstrate that microgreens have evolved into a multidisciplinary research topic encompassing plant science, food chemistry, nutrition, and controlled-environment agriculture.

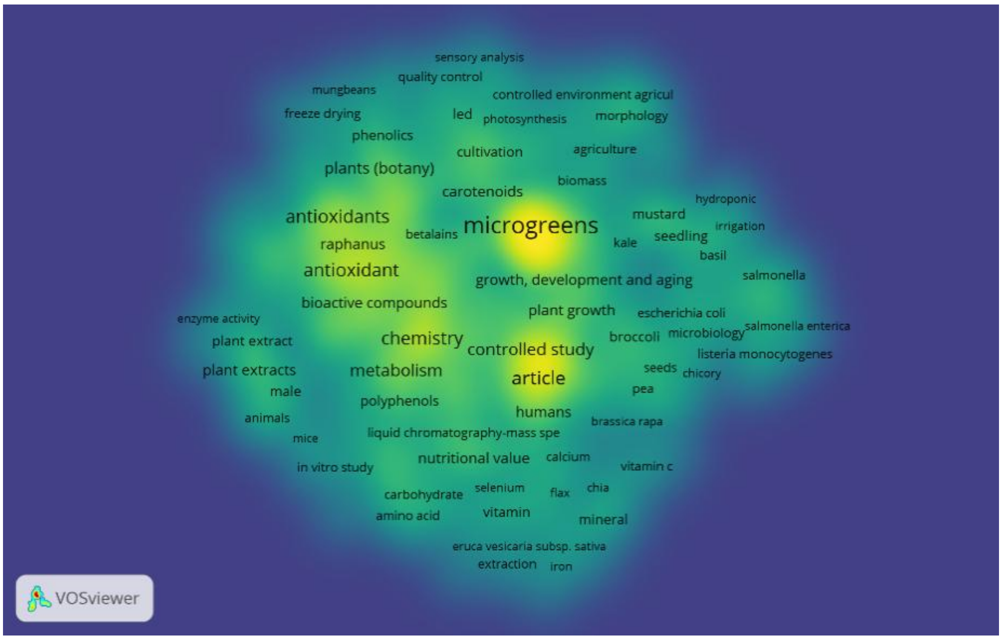


Fig. 5. Density visualization of all-keyword co-occurrence in global microgreen research (VOSviewer)

Several nutritional and phytochemical-related keywords, including carotenoids, polyphenols, phenolics, vitamin C, minerals, and bioactive compounds, are located within high-density regions surrounding the central node. This finding suggests that improving nutritional quality and enhancing functional compounds remain the primary objectives of contemporary microgreen research. Likewise, cultivation-related keywords such as controlled environment agriculture, LED, hydroponics, photosynthesis, and biomass further indicate increasing research interest in optimizing production systems through advanced cultivation technologies.

The density map also highlights the presence of food safety and microbiological themes, represented by keywords such as Listeria monocytogenes, Escherichia coli, Salmonella, and microbiology. Although these topics occupy relatively smaller density areas than nutritional studies, their occurrence reflects growing concern regarding the microbial safety of fresh microgreen products intended for human consumption. Furthermore, species-specific keywords, including broccoli, mustard, kale, radish, mungbeans, pea, chia, and basil, indicate that research has expanded across a wide range of commercially important microgreen species. This diversity suggests increasing efforts to evaluate species-specific nutritional characteristics and cultivation performance.

Despite the broad thematic coverage, the visualization reveals no dominant keywords associated with rice washing water, recycled household wastewater, or domestic organic waste utilization. The absence of these sustainability-related terms suggests that the application of household-derived organic resources as alternative nutrient inputs remains insufficiently explored within the global microgreen research landscape. Therefore, the present study contributes to addressing this research gap by experimentally evaluating the potential of rice washing water as a sustainable nutrient source for mung bean microgreen production.

3.5 Technical aspects of microgreen cultivation

To contextualise the present experiment within the broader technical framework of microgreen production, several interacting parameters must be considered. Microgreen cultivation performance is governed by several interacting technical parameters, namely the design of the growing, the physical and chemical properties of the growing medium, light management, irrigation, and, most critically, the type and concentration of nutrient input supplied during the short cultivation cycle. Variations in tray depth, drainage, and material have been reported to influence root aeration and water-holding capacity, thereby affecting germination uniformity and stand establishment, while substrate selection, ranging from soil and soilless organic media to inert materials such as cotton or hydroponic, determines the extent to which background nutrients are available to the crop independent of applied inputs (Gunjal et al., 2024). Among these parameters, fertilization and nutrient management have consistently been identified as one of the most decisive determinants of microgreen yield and quality, since fertigation strategy directly regulates the resources available for biomass accumulation and phytochemical synthesis during the brief cotyledon-stage growth (Paglialunga et al., 2023).

The bibliometric mapping described above indicates that global microgreen research has concentrated heavily on light-based cultivation technologies and phytochemical profiling, while circular or household-derived nutrient inputs, such as organic waste-based composts and washing water by-products, remain comparatively underrepresented despite their demonstrated relevance to sustainable substrate and fertilization management (Poudel et al., 2023). This imbalance indicates that, although the technical importance of fertilization for microgreen nutrition is well established, empirical evidence on low-cost, household-derived nutrient alternatives remains limited. Rice washing water, as a daily household by-product in Indonesia, contains residual starch, minerals, and organic compounds that have been reported to possess plant growth-supporting properties (Nabayi et al., 2021), although its elemental composition, including potential trace contaminants, requires further characterization (Wełna et al., 2023). These considerations collectively justify the experiment conducted in this study, in which rice washing water was evaluated as an alternative fertilization input for mung bean microgreens, thereby connecting the identified bibliometric research gap to a targeted empirical test of a circular, household-scale nutrient source.

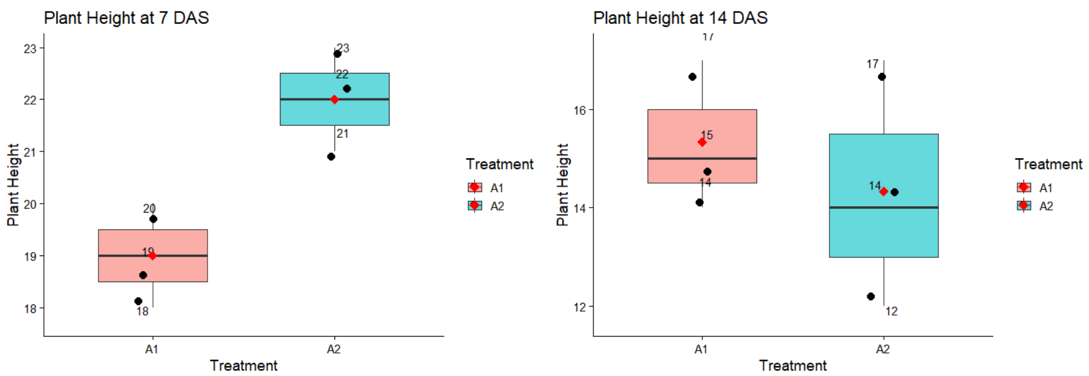
3.5 Technique analyze

3.5.1 Plant height

Technical analyze was carried out by germinating mung beans with two treatments. The first treatment used plain water and the second used rice washing water. The treatments showed different effects on each observation variable. The descriptive analysis indicated that treatment A2 promoted greater early plant height than treatment A1 at 7 days after sowing (DAS). Plants receiving treatment A2 reached an average height of 14.33 ± 2.52 cm, whereas those under treatment A1 averaged 15.33 ± 1.53 cm representing an increase of approximately 15.8%. The independent-samples t-test confirmed that this difference was statistically significant ($p = 0.021$), suggesting that treatment A2 stimulated faster initial vertical growth during the first week of cultivation.

However, this growth advantage was not maintained until 14 DAS. At this stage, the mean plant height was 19.00 ± 1.00 cm for treatment A1 and 22.00 ± 1.00 cm for treatment A2, and no statistically significant difference was detected ($p = 0.594$). The convergence in plant height indicates that the initial growth stimulation observed in treatment A2 was temporary and did not translate into sustained differences during the later growth stage.

The reduction in average plant height between 7 and 14 DAS in both treatments likely reflects the harvesting stage of microgreens rather than actual stem shrinkage. Because measurements were conducted on different plant batches harvested at different times, the observed values represent separate developmental observations instead of continuous growth of the same individual plants. Therefore, the comparison should be interpreted as differences in plant performance at each harvest stage rather than longitudinal growth dynamics.



(a) (b)

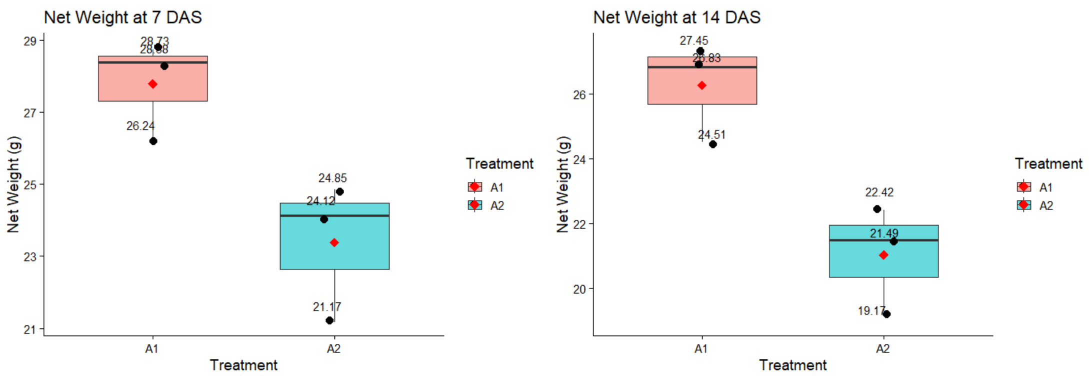
Fig. 6. Mean plant height (cm) of mung bean microgreens under plain-water (A1) and rice washing water (A2) treatment. (a) 7 days after sowing; (b) 14 days after sowing

Overall, the results suggest that treatment A2 primarily affected early vegetative elongation, whereas both treatments exhibited comparable plant height by the final harvest period. Plant height is a measurement variable often observed as an indicator of plant growth due to the influence of genetics, environment, and cultivation management. Increased plant height indicates a plant's ability to undergo the vegetative phase through the generative and harvest phases (Anhar et al., 2022). This shows that rice washing water has a stimulating effect on early plant growth, (Ziliwu, 2025) said this rapid growth is closely related to the nutritional content of rice washing water, such as starch, vitamin B1, nitrogen, phosphorus, and potassium. Starch serves as an energy source, while vitamin B1 supports metabolism and root formation. Nitrogen stimulates leaf growth, phosphorus strengthens roots, and potassium aids in water transport and stem strengthening. These nutrients accelerate the physiological activity of plants from germination to vegetative growth. Furthermore, rice washing water contains the hormones auxin and cytokinin. Auxin accelerates cell elongation, and cytokinin plays a role in cell division (cytokinesis) and promotes root and stem formation, as well as root and stem branching (Simatupang et al., 2024). Aini et al. (2023) showed that giving several concentrations of rice washing water had a significant effect on the height of chili plants, as seen in control plants that were not given rice washing water has delayed growth.

3.5.2 Net weight

Net weight showed a contrasting response compared with plant height. At 7 DAS, treatment A1 produced a significantly higher fresh biomass (27.78 ± 1.35 g) than treatment A2 (23.38 ± 1.95 g), corresponding to an increase of approximately 18.8% ($p = 0.038$). The superiority of treatment A1 became even more evident at 14 DAS. Plants under treatment A1 achieved an average net weight of 26.26 ± 1.55 g, whereas treatment A2 produced only 21.03 ± 1.67 g, representing a biomass increase of nearly 25%. This difference was statistically significant ($p = 0.017$), indicating that treatment A1 consistently enhanced biomass accumulation throughout the cultivation period.

Interestingly, although treatment A2 promoted greater plant height during the early growth stage, this advantage was not accompanied by greater biomass production. Taller plants therefore did not necessarily produce higher fresh weight, suggesting that stem elongation and biomass accumulation were influenced differently by the treatments. In contrast, treatment A1 appeared to allocate more assimilates toward tissue development, resulting in heavier harvested plants despite their relatively shorter stature during the first week.



(a) (b)

Fig. 7. Mean net height (g) of mung bean microgreens under plain-water (A1) and rice washing water (A2) treatments. (a) 7 days after sowing; (b) 14 days after sowing

These findings indicate that biomass accumulation may be a more sensitive indicator of treatment effectiveness than plant height alone, particularly when evaluating crop productivity. For commercial microgreen production, fresh biomass is generally considered the primary economic trait because it directly determines marketable yield. Fadhilah et al. (2024) research shows that the age of plant harvest will affect the weight of the plant. Anhar et al. (2022) showed that mung bean plants experience a slow growth phase during the first to third weeks because they don't yet have many leaves, so photosynthesis isn't optimal. But Microgreens, defined as young veggies harvested between 5 - 21 days (about 3 weeks) after germination, exhibit a unique profile that distinguishes them from their mature counterparts.

3.5.3 Assumption testing

Prior to hypothesis testing, the assumptions of parametric analysis were evaluated (Fig. 7). The Shapiro–Wilk test indicated that all variables followed a normal distribution ($p > 0.05$), while Levene's test demonstrated homogeneity of variance across treatments for all measured parameters ($p > 0.05$). These results satisfied the assumptions required for independent-samples t-tests. As an additional robustness check, non-parametric Wilcoxon rank-sum tests were also performed. Unlike the t-tests, the Wilcoxon tests did not detect statistically significant differences between treatments ($p = 0.10$ for plant height at 7 DAS and both net weight measurements). This discrepancy is most likely attributable to the extremely small sample size (three replicates per treatment), which substantially limits the statistical power of rank-based tests. Consequently, although the parametric assumptions were met, the statistical findings should be interpreted cautiously, and future studies with larger sample sizes are recommended to improve the reliability and generalizability of the observed treatment effects. Being fresh-cut product, microgreens have a relatively very short shelf life, which does vary depending upon the species and the quick post-harvest quality deterioration is also due to their high surface area to volume ratio, delicate leaves, and high respiration rate (Priti et al., 2022). Saputra et al. (2023) showed the effect of The treatment of rice washing water fermentation had a significant effect on dry hull, pod length, pod weight per planting hole and pod weight per plant. Furthemore Musliadi et al. (2025) said Several factors contribute to the decline in mung bean production on farmers' land, including: limited availability of superior varieties that are adaptive to environmental changes, unoptimized cultivation techniques, disturbances from plant pests (OPT) that reduce crop yields, socio-economic constraints that affect farmers' access to technology and production inputs, the impact of climate change that causes unstable growing conditions, and imbalances in water availability, either excess or deficiency, which results in water stress in plants.

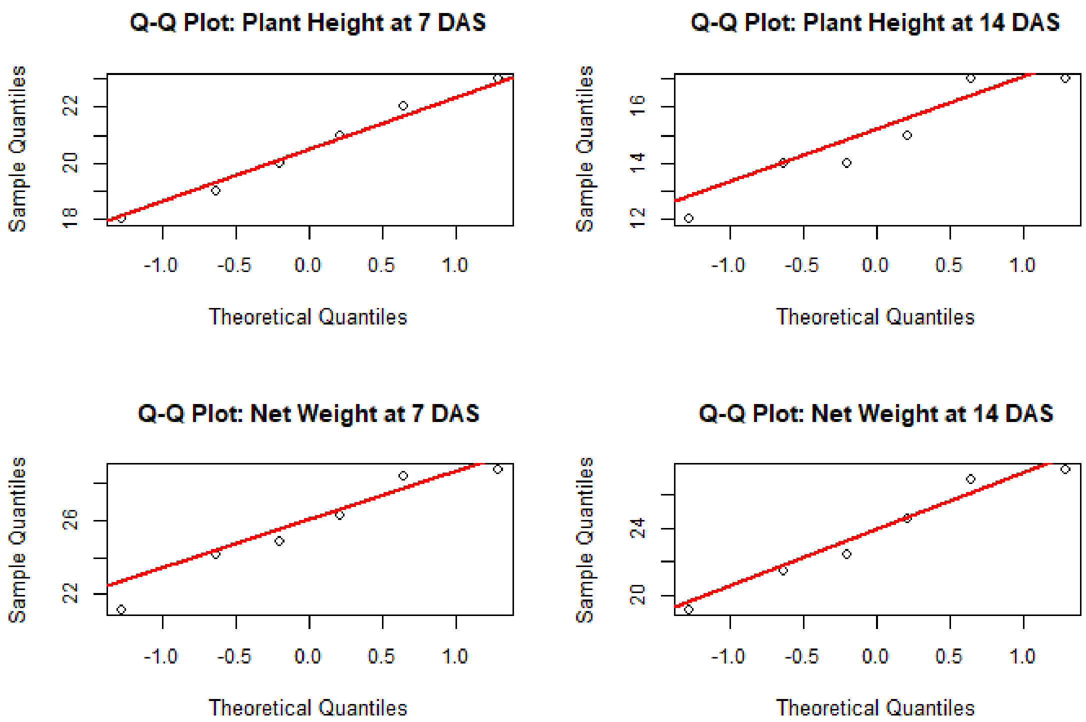


Fig. 7. Q-Q plot mean heigt (cm) and fresh net weight (g) of mung bean microgreens under plain-water (A1) and rice washing water (A2) treatments at 7 and 14 days after sowing

This study bridges the gap between bibliometric evidence and experimental validation. While global microgreen research has increasingly emphasized nutritional enhancement, controlled-environment cultivation, and advanced production technologies, the reuse of household organic by-products has remained largely overlooked. The present findings demonstrate that rice washing water can stimulate early vegetative growth but is insufficient to maximize biomass production under nutrient-free conditions. These results suggest that rice washing water should be regarded not as a complete nutrient replacement but as a complementary input whose effectiveness is influenced by substrate characteristics and crop developmental stage. Consequently, this study contributes to the emerging field of sustainable urban agriculture by providing one of the first experimental evaluations of rice washing water within a household-scale microgreen production system, offering a practical foundation for future research on circular resource utilization in food production.

4. Conclusions

This study combined bibliometric analysis with experimental validation to address a clearly identified gap in global microgreen research: the underexploration of household-derived organic by-products as sustainable cultivation inputs. Mapping of Scopus-indexed publications showed that microgreen research has grown into a multidisciplinary field centered on controlled-environment cultivation, phytochemical enhancement, nutritional quality, and food safety, led by the United States, India, and Italy, while Indonesia, despite ranking among the top ten contributing countries, showed comparatively limited citation impact and collaboration strength. Importantly, the co-occurrence, overlay, and density visualizations consistently revealed an absence of research themes related to rice washing water or other domestic organic waste utilization, confirming that sustainable nutrient management using household by-products remains a significant and persistent research gap that this study sought to address experimentally.

The experimental findings demonstrated that rice washing water significantly enhanced early shoot elongation at 7 days after sowing but did not translate into greater biomass accumulation, with plain water consistently producing higher fresh weight at both 7 and 14 days after sowing, and the early height advantage of rice washing water not sustained by the final harvest stage. These results indicate that rice washing water functions as a stimulant of early vegetative growth rather than a complete nutrient substitute, with its effectiveness depending on developmental stage and growing medium conditions; accordingly, it is best regarded as a complementary, zero-waste input for household-scale microgreen production rather than a standalone nutrient source, providing a practical foundation for future research on circular resource utilization in sustainable urban agriculture. Building on the broader biological activity of rice washing water documented in other systems, as a microbial growth medium, a fermentation-enhanced biofertilizer, and a partial hydroponic nutrient substitute, future work should test fermented rice washing water, nutrient-supplemented cotton substrates, or combined organic media to determine whether the early growth-promoting effect observed here can be extended into measurable biomass gains.

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Author Contribution
Conceptualization, N.I.D.A.; Methodology, N.I.D.A. and D.P.P.; Software, N.I.D.A.; Validation, N.I.D.A. and D.P.P.; Formal Analysis, N.I.D.A. and D.P.P.; Investigation, N.I.D.A and D.P.P.; Resources, N.I.D.A., D.P.P. and S.I.; Data Curation, N.I.D.A. and D.P.P.; Writing – Original Draft Preparation, N.I.D.A., D.P.P. and S.I.; Writing – Review & Editing, N.I.D.A., D.P.P. and S.I.; Visualization, N.I.D.A.; Supervision, N.I.D.A. and D.P.P.; Project Administration, N.I.D.A. and D.P.P.; and Funding Acquisition, N.I.D.A. and D.P.P.

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During the preparation of this work, the author used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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