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Master II – Natural and Life Sciences

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Stimulatory Effects of Some Organic Fertilizers on Chili Pepper

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Thank you all.

Dedication

To my mother,

For your unconditional love, your prayers, and your endless encouragement, your presence in my life is a blessing beyond words.

To my father,

For your silent strength, your sacrifices, and the values you've instilled in me, thank you for being my greatest role model.

To my brother, my sisters, and all my family,

For always believing in me and being a source of love and reassurance.

To my friends,

For your constant support, kind words, and for making this journey lighter.

This work is dedicated to you all, with love and gratitude.

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Table of content

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PDF-XChange Viewer Click to buy NOW! www.docu-track.com

List of figures

PDF-XChange Viewer Click to buy NOW! www.docu-track.com

List of tables

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List of abbreviations

NFT : Nutrient Film Technique

TM : Control (Témoin)

MVC: Vermicompost Mix

MI-MR-F: Fermented Mix of Millet and Mulberry

MI-PO-F: Fermented Mix of Millet and Poplar

MI-RATIO-F: Fermented Mix of Plant Materials (Ratio formula)

RWC: Relative Water Content

CH: Chlorophyll

LPA : Shoot Length (Longueur de la Partie Aérienne)

LPR : Root Length (Longueur de la Partie Racinaire)

NBF : Number of Leaves (Nombre de Feuilles)

PFA : Fresh Weight of Aerial Parts (Poids Frais de la Partie Aérienne)

PFR : Fresh Weight of Roots (Poids Frais de la Partie Racinaire)

PSA : Dry Weight of Aerial Parts (Poids Sec de la Partie Aérienne)

PSR : Dry Weight of Roots (Poids Sec de la Partie Racinaire)

PCA / ACP : Principal Component Analysis / Analyse en Composantes Principales

ANOVA: Analysis of Variance

SPAD: Soil Plant Analysis Development (Chlorophyll Index Reading)

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Stimulatory Effects of Fermented Biofertilizers on Capsicum spp. Under Soilless Conditions

Abstract

The growing use of biofertilizers in modern agriculture is driven by the need to enhance plant growth while minimizing the environmental and health risks associated with chemical inputs. Their integration into soilless cultivation systems is seen as a promising and sustainable alternative.

This study was conducted on hot pepper (*Capsicum spp.*) to assess the effects of fermented vermicompost-based bioproducts, both organic and plant-derived, on plant development, reproductive behaviour, and physiological condition. The experiment was carried out in a hydroponic system using the Nutrient Film Technique (NFT), and included five distinct treatment blocks, each receiving a different biofertilizer formulation.

The results showed that the bioproducts had varying effects depending on the treatment applied. The MI-MR-F treatment promoted shoot growth, leaf production, and flowering, while the MI-PO-F treatment supported stronger root development and improved leaf chlorophyll content. Overall, these organic formulations demonstrated comparable or even superior performance to conventional practices in many of the parameters studied.

Keywords

Biofertilizer, Hydroponics, Photosynthesis, Sustainable agriculture, Vegetative stimulation.

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Effets stimulants des biofertilisants fermentés sur Capsicum spp. en conditions sans sol

Résumé

L'utilisation croissante des biofertilisants en agriculture moderne est motivée par la nécessité de stimuler la croissance des plantes tout en réduisant les risques environnementaux et sanitaires liés aux intrants chimiques. Leur intégration dans les systèmes de culture hors-sol est considérée comme une alternative prometteuse et durable.

Cette étude a été menée sur le piment fort (Capsicum spp.) afin d'évaluer les effets de bioproduits à base de vermicompost fermenté, d'origine organique et végétale, sur le développement des plantes, le comportement reproducteur et l'état physiologique. L'expérimentation a été réalisée en système hydroponique selon la technique du film nutritif (NFT), avec cinq blocs de traitement distincts, chacun recevant une formulation de biofertilisant différente.

Les résultats ont montré que les bioproduits ont eu des effets variables selon les traitements appliqués. Le traitement MI-MR-F a favorisé la croissance aérienne, la production foliaire et la floraison, tandis que le traitement MI-PO-F a soutenu un développement racinaire plus important et une amélioration de la teneur en chlorophylle des feuilles. Globalement, ces formulations organiques ont présenté des performances comparables, voire supérieures, aux pratiques conventionnelles pour plusieurs des paramètres étudiés.

Mots-clés

Biofertilisant, Hydroponie, Photosynthèse, Agriculture durable, Stimulation végétative.

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التأثيرات المحفزة للأسمدة الحيوية المخمرة على أنواع الفلفل الحار في ظروف الزراعة بدون تربة

ملخص

تزداد أهمية الأسمدة الحيوية في الزراعة الحديثة بفضل قدرتها على تعزيز نمو النباتات مع تقليل الآثار السلبية المرتبطة باستخدام الأسمدة الكيميائية. ويُعد إدماج هذه المنتجات في أنظمة الزراعة خارج التربة خياراً مستداماً وواعداً.

من أجل تقييم تأثير منتجات حيوية سائلة مستخلصة من الفيرمي كومبوست المخمر، من أصل نباتي وعضوي، على النمو والتكاثر والحالة الفسيولوجية للنبات، أُجريت هذه الدراسة على نبات الفلفل (*Capsicum spp.*). تم تنفيذ التجربة في نظام زراعة مائية بتقنية الغشاء المغذي (NFT)، باستخدام خمسة كتل تجريبية، كل منها تلقى تركيبة مختلفة من السماد الحيوي

أظهرت النتائج أن تأثير المعاملات كان متبايناً حسب نوع التسميد الحيوي. حيث ساهم المعامل MI-MR-F في تعزيز فعالية أكبر في تطوير الجذور وتحسين نمو السوق وزيادة عدد الأوراق والأزهار، بينما أظهر المعامل MI-PO-F محتوى الكلوروفيل في الأوراق. بشكل عام، أثبتت هذه المنتجات الحيوية أداءً مشابهاً، بل وأفضل في بعض الأحيان، من الأسمدة التقليدية في معظم المؤشرات المدروسة

الكلمات المفتاحية

الزراعة المائية، التحفيز الخضري، التركيب الضوئي، الزراعة المستدامة، التسميد الحي

General Introduction

Feeding a growing population while protecting natural ecosystems is one of the major challenges of our time. With global food demand expected to rise significantly by 2030, agriculture is under pressure not just to increase output, but to do so without further damaging the environment (Springmann *et al.*, 2018). In many regions, including North Africa, this challenge is amplified by water scarcity, land degradation, and the growing need for sustainable intensification.

Over the past century, agricultural systems have relied heavily on synthetic fertilizers and chemical inputs derived from non-renewable resources. While these substances have helped increase yields in the short term, their long-term effects include soil degradation, water pollution, biodiversity loss, and rising greenhouse gas emissions (Amundson *et al.*, 2015; Zhang *et al.*, 2021). Beyond environmental harm, growing evidence points to serious public health risks from agrochemical residues found in food and contaminated water, especially in rural areas with limited access to safe water and sanitation (Mostafalou & Abdollahi, 2013). These combined effects threaten not only ecosystems but also the sustainability of food systems and human well-being.

In response to these concerns, the agricultural sector is increasingly turning toward ecological intensification—a strategy that aims to maintain high productivity while reducing external chemical inputs and restoring ecological function (Tittonell, 2024; Vanlauwe *et al.,* 2019). Among the key components of this shift are organic and biologically active inputs, such as compost, manure, and biofertilizers, which promote soil health and plant growth through natural processes.

Vermicompost, a nutrient-rich product of organic matter decomposition by earthworms, is one such input. It has been shown to improve soil structure, enhance microbial activity, and supply essential nutrients in plant-available forms (Singh *et al.,* 2022).

Its liquid derivatives vermicompost tea and fermented vermicompost extracts are gaining interest due to their ease of application and high concentrations of beneficial microorganisms, enzymes, humic acids, and plant-growth regulators (Rajpal *et al.,* 2021; Nourbakhsh & Khoshru, 2023). These bioproducts have been reported to enhance photosynthesis, stimulate plant metabolism, and improve tolerance to abiotic stress.

Although the benefits of vermicompost-based products have been demonstrated in several crops, their impact on hot pepper (*Capsicum annuum* L.), particularly under hydroponic conditions, remains insufficiently explored. Yet this crop is of considerable agronomic and economic value in many regions, including Algeria. Hydroponic cultivation especially in water-limited areas offers a promising pathway for sustainable agriculture, allowing precise control of nutrients and reducing water loss. Integrating biofertilizers into hydroponic systems could provide a dual benefit: enhancing plant performance while minimizing chemical use.

This study aims to evaluate the effects of fermented vermicompost-based bioproducts on the growth, reproduction, and physiological responses of hot pepper plants grown hydroponically. Measurements focused on shoot and root development, leaf production, reproductive output (flowers, buds, and fruits), and physiological parameters such as chlorophyll content, water retention. By testing natural alternatives to conventional fertilization in a controlled, soilless system, this research contributes to the development of resilient and sustainable crop production practices.

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Chapter I: Literature Review

1. Fertilization and Mineral Nutrition

1.1 Principles and Objectives of Fertilization

Fertilization is an important agronomic operation aimed at supplying plants with nutrients through the soil or growing substrate to facilitate their development and maximize yield. Fertilization replenishes inherent soil nutrient deficiencies, improves the physicochemical and biological condition of the root milieu, and strengthens well-integrated crop production (Zidane, 1989; Schvartz *et al.,* 2005). It requires fine appreciation of different factors like soil type, climate, crop phenological growth phases, irrigation management, and nutrient interactions. The overall objectives of fertilization are to ensure a consistent balanced supply of nutrients during the period of crop growth, enhance yield and quality, prevent nutritional disorders, minimize environmental risks resulting from nutrient losses, and maintain long-term soil fertility (Soltner, 2003). In accordance with crop needs and agricultural practices, fertilization programs could incorporate mineral, organic, or organo-mineral combined sources.

1.2 Mineral Nutrition of Cultivated Plants

Plants depend on a variety of mineral elements in order to fulfill their physiological and biochemical functions. These nutrients are primarily absorbed in ionic forms by the root system from the soil solution. The bioavailability and uptake efficiency of these mineral elements are influenced by a variety of edaphic factors such as microbial activity, soil pH, moisture level, and temperature (Mengel & Kirkby, 2001). Mineral nutrition is essential at every phase of plant growth, starting from germination to vegetative growth and reproductive phases. Mineral nutrition aids enzymatic reactions and energy transport, cell division and extension, photosynthetic processes and chlorophyll biosynthesis, and flower initiation, fruiting, and seed formation. Nutrient disorders, either deficiency or toxicity, can go against metabolism and drastically lower crop yields.

1.3 Role of Macronutrients: Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, and Sulfur

Macronutrients occur in relatively large quantities and all have specified and necessary physiological functions. Nitrogen is a structural component of amino acids, proteins, nucleic acids, and chlorophyll and therefore promotes vegetative biomass increase. Phosphorus facilitates root growth, energy transfer from and by ATP, and plant vigor early on. Potassium regulates osmotic adjustment, activates numerous enzymes, and enhances fruit quality and stress resistance. Calcium contributes to structural functions in cell walls and membranes, supporting cell division and integrity. Magnesium is the central atom in chlorophyll molecules and plays a role in activating enzymes and photosynthesis. Sulfur is found as a component of sulfur amino acids and coenzymes and plays a critical role in protein construction and metabolic activities (Fageria *et al.,* 2011; Marschner, 2012). The precise regulation of these macronutrients is critical to the attainment of optimal plant growth and production.

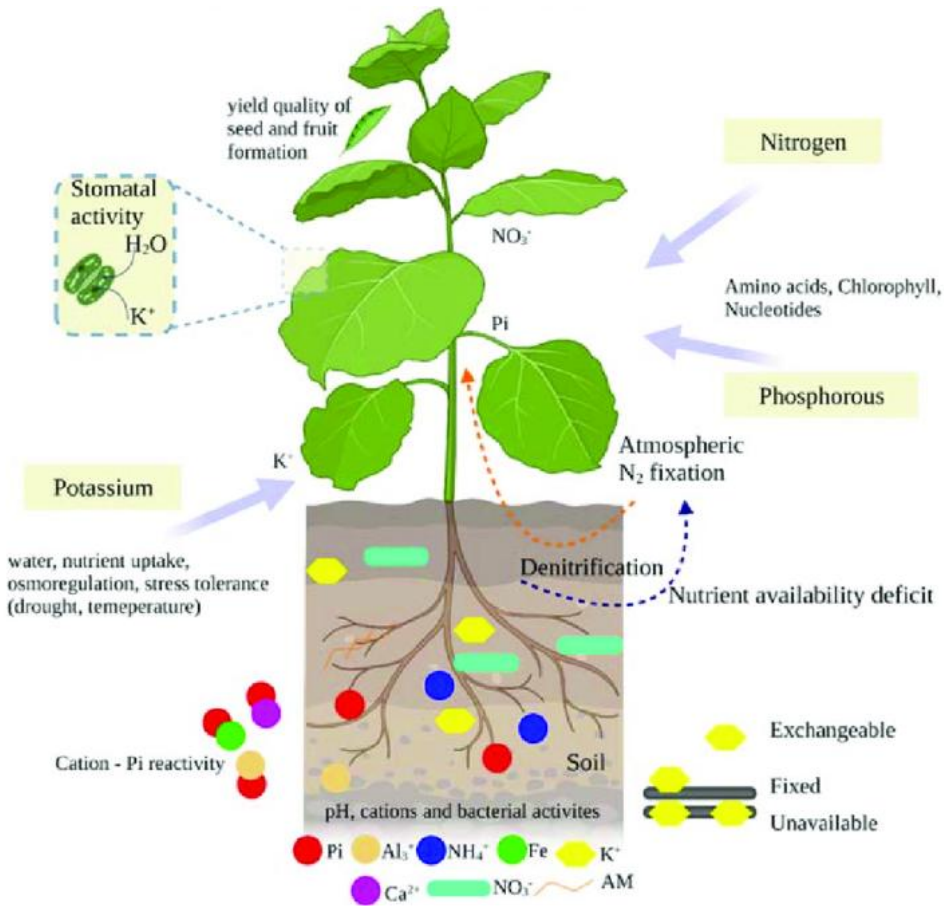

Figure1: Role of macronutrient in plant growth (Jose, 2023)

1.4 Importance of Micronutrients: Iron, Zinc, Manganese, and Others

Micronutrients, although required in small amounts, are equally vital for plant health as they act as cofactors for enzymatic and physiological processes. Iron is required for chlorophyll biosynthesis and electron transport during respiration. Zinc participates in auxin metabolism, protein synthesis, and enzymatic reactions. Manganese participates in photosynthesis, nitrogen assimilation, and antioxidant defence mechanisms. The remaining micronutrients such as copper, boron, molybdenum, and chlorine have specialized roles in reproductive development, cell wall synthesis, and in various metabolic processes (Taiz *et al.*, 2015).

Micronutrient deficiencies in plants are often associated with symptoms such as chlorosis, necrosis, reduced growth, and reproductive failure, especially in soilless systems where nutrient availability must be carefully managed (Mengel & Kirkby, 2001; Marschner, 2012).

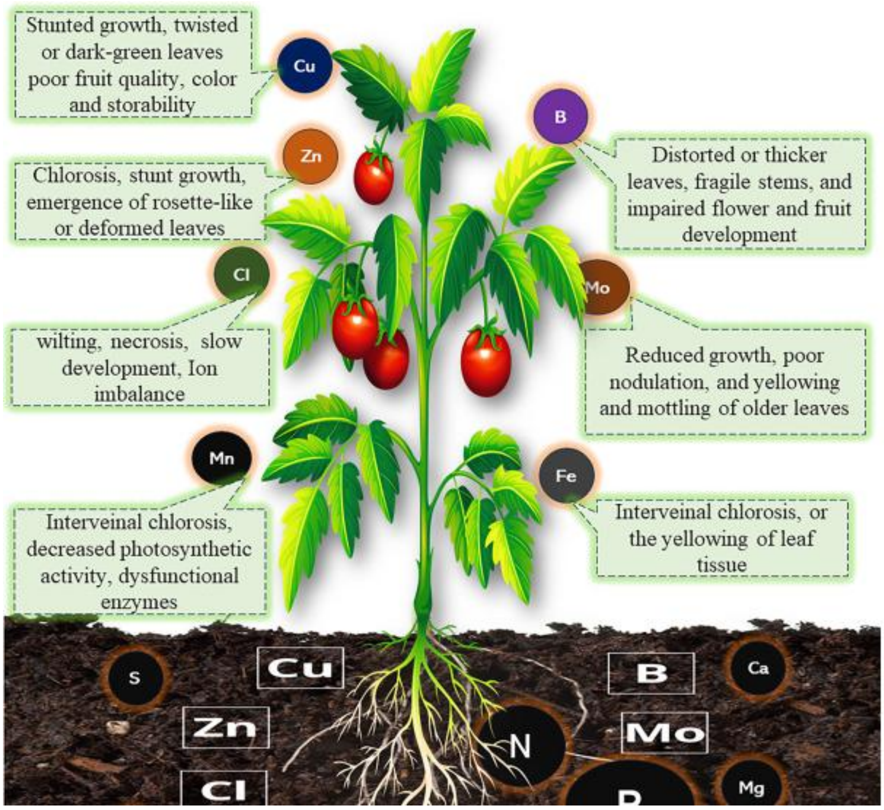

Figure2: Role of micronutrient in plant growth (Nazir, 2024)

1.5 Organo-Mineral Fertilization: Effects on Plant Growth

Organo-mineral fertilization integrates the benefits of organic and mineral nutrient sources, thus forming the chemical as well as the biological properties of the soil and affording direct access to nutrients. The integrated method stabilizes the structure of the soil, boosts microbial diversity, raises the nutrient-retaining capacity, and permits controlled release of nutrients. Hence, it favors root development and maximizes the effectiveness of nutrient intake, but reduces the environmental hazard compared to single mineral fertilization (Mabrouk *et al.*, 2022).

Experimental findings indicate that plants treated with organo-mineral fertilizers often show improved biomass production, enhanced tolerance to abiotic stress, and sustained yields under intensive cultivation (Mabrouk *et al.,* 2022).

2. Biofertilization

2.1 Definition of Biofertilizers

Biofertilizers are active biological preparations of live or latent microorganism strains that promote the availability and absorption of major nutrients in plants. In contrast to synthetic fertilizers that provide nutrients in chemical form directly, biofertilizers fertilize the soil by carrying out natural biological processes like nitrogen fixation, phosphate solubilization, and phytohormone production. These mechanisms not only favor nutrient availability but also microbial diversity and soil health in the long term (Vessey, 2003; Bashan *et al.,* 2014).

Biofertilization represents a sustainable alternative to chemical inputs and a main constituent of agroecological systems, especially in the context of organic and low-input agriculture.

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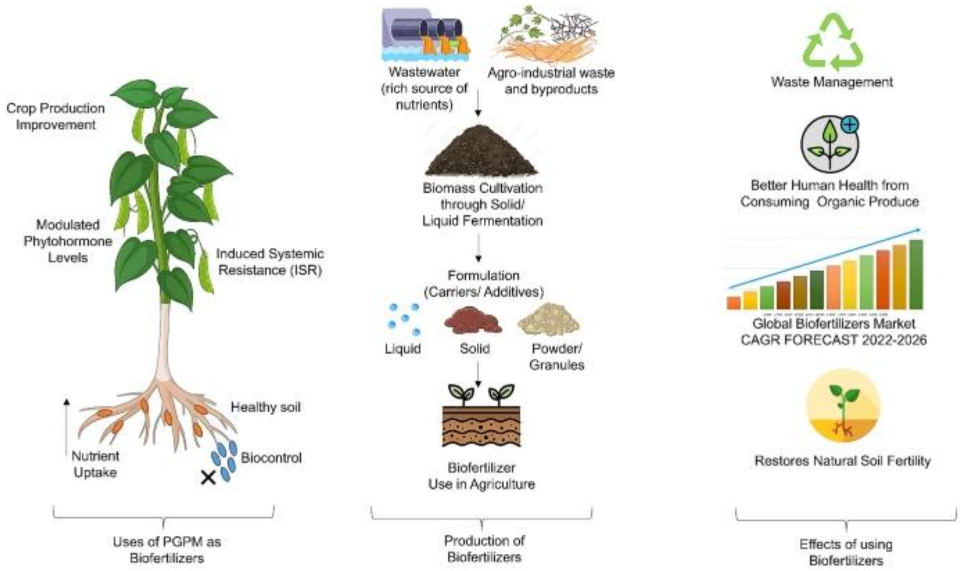

Figure3: Role of micronutrient in plant growth (Bagga, 2024)

2.2 Classification of Biofertilizers

Biofertilizers are usually divided based on the type of useful microbes they contain and their primary mode of activity:

a/ Microbial Biofertilizers: Those strains that have been well studied, such as Rhizobium, Azotobacter, and Azospirillum, which can fix atmospheric nitrogen, come under this category. Phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), and arbuscular mycorrhizal fungi (AMF) also come under this category. These microorganisms live in the rhizosphere or form a symbiotic relationship with plant roots and thereby enhance nutrient availability and utilization (Kumar *et al.,* 2020; Sharma *et al.,* 2021).

b/ Organic Biofertilizers: These include composts, vermicomposts, and fermented organic substrates that are naturally enriched with useful microorganisms and organic matter. They not only supply nutrients but also improve soil physicochemical properties and stimulate biological activity.

c/ Green Manures: Legume plants such as clover or vetch are planted and then incorporated back into the soil, adding organic matter and biologically fixed nitrogen.

This has particular use for promoting soil fertility in poor or degraded soils (Bhattacharyya & Jha, 2012).

Each type of biofertilizer has a particular function, and their effectiveness is often enhanced when used in combination.

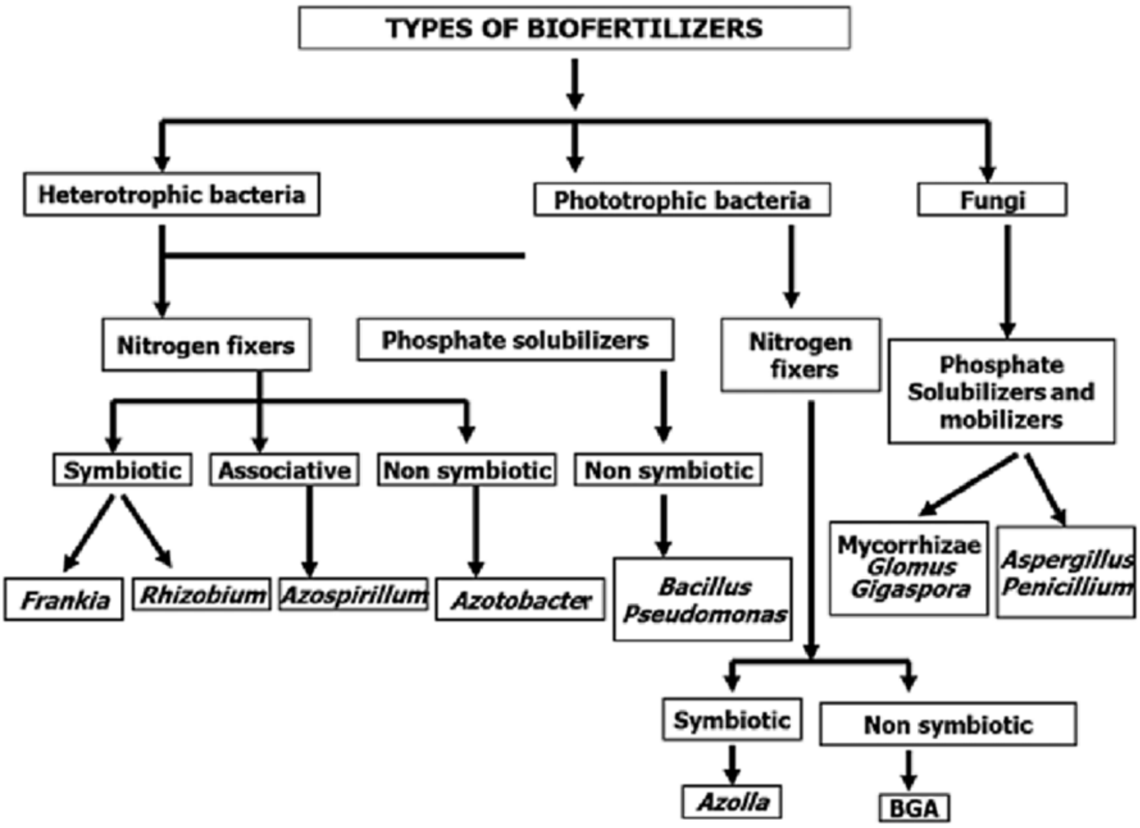

Figure 4: types of biofertilizers and their functions (Motsara *et al.*1995)

2.3 Compost

2.3.1 and Composting Process

Composting is a microbial process in which microorganisms cause aerobic decomposition of organic residues to form a stable humus-like substance known as compost. Composting goes through four successive stages: mesophilic, thermophilic, cooling, and maturation. Each stage is characterized by typical microbial populations as well as characteristic temperature and oxygen regimes, all of which contribute towards breaking down organic material into a nutrient-rich amendment (Bernal *et al.*, 2009).

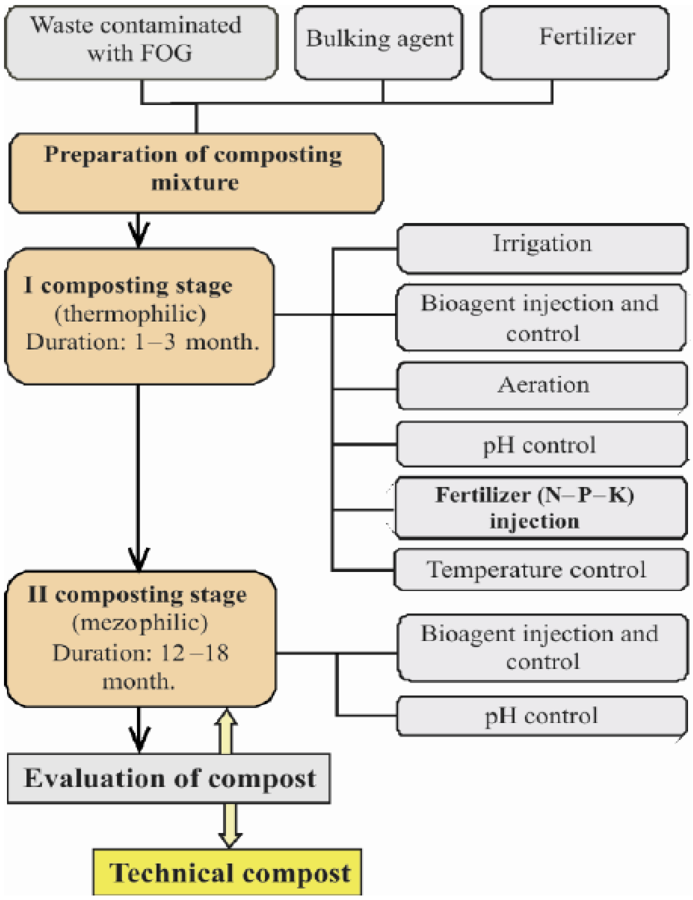

Figure 5: the stages of composting: mesophilic, thermophilic, cooling, and maturation. (Grigiskis *et al.,* 2010)

2.3.2 Raw Material Used

Organic plant wastes or crop residues, animal manure, food waste, and green waste are typical feedstocks used by compost plants. The carbon-to-nitrogen (C: N) ratio of materials plays a crucial role in microbial activity and compost effectiveness with an ideal ratio ranging from 25:1 to 30:1 (de Bertoldi *et al.,* 1983).

2.3.3 Agronomic Value and Soil Fertility

Compost has significant contributions to soil structuring, water retention capacity, and cation exchange capacity (CEC). Compost also increases microbial biomass and enzymatic activity and hence accelerates the rate of nutrient mineralization and biological health of the soil (Liu *et al.,* 2018; Arancon *et al.,* 2004).

2.3.4 Effects on Plant Growth

Its application has been shown to increase root biomass, increase nutrient uptake efficiency, and improve yields. It also increases plant resistance against biotic and abiotic stresses by strengthening natural defense structures and improving overall soil-plant relationships (Zhang *et al.,* 2020).

2.3.5 Comparison to Other Organic Amendments

Compared to raw or green manures, compost is a stable, older product with reduced phytotoxicity and more even pattern of nutrient release. Its use reduces nutrient leaching and ensures long-term fertility without the risks inherent in immaturity or imbalance of organic matter (Bernal *et al.,* 2009).

2.4 Vermicompost

2.4.1 Definition and Principles

Vermicomposting is the biological decay process mediated by earthworms-Eisenia fetida in particular-which consume and fragment organic matter and, as a consequence, accelerate the microbial decay process. The end product, vermicompost, is rich in nutrients, fine-textured, and biologically active, making it particularly effective in the enhancement of plant vigor (Edwards *et al.,* 2011).

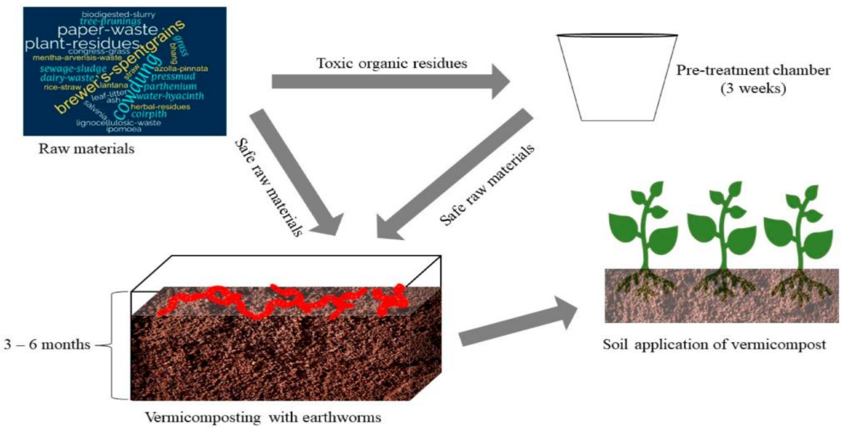

Figure 6: Schematic illustration of the vermicomposting process. The earthworms on top of the vermicomposting bed are shown in red color (Oyege, 2023).

2.4.2 Role of Earthworms

Earthworms perform an important action by ingesting organic matter and excreting that material as castings. These castings are very rich in nutrients most available to plants and humic compounds. Furthermore, by the simple act of moving organisms aerating the substrate and enhancing microbial colonization, it also increases organic matter transformation rates (Domínguez & Edwards, 2011).

2.4.3 Composition and Properties

Vermicompost is characterized by higher concentrations of N, P, K, as well as important micronutrients like Fe, Zn, and Mn. It contains humic substances and a diverse microbial population that enhances soil fertility and stimulates plant growth (Arancon *et al.,* 2004).

2.4.4 Differences from Traditional Compost

Vermicompost has finer granularity, more soluble nutrients, and greater microbial activity, compared to conventional compost. These characteristics make it more effective for rapid plant responses and soil restoration (Edwards & Arancon, 2004).

2.4.5 Agronomic and Environmental Advantages

Vermicomposting improves soil porosity, water retention and nutrient use efficiency, while enabling waste recycling and decreasing greenhouse gas emissions. It is considered an eco-friendly way of managing organic waste and enhancing agricultural productivity (Suthar, 2009)

2.5 Mechanisms of Action and Soil Effects

The mechanisms through which biofertilizers operate are varied and well-studied. They include:

- **Biological Nitrogen Fixation:** Diazotrophic bacteria convert atmospheric nitrogen (N_2) to ammonium (NH4 +), which plants can utilize. This process is crucial in legume-based systems (Gyaneshwar *et al.,* 2002).

- **Phosphate Solubilization:** Certain bacteria secrete organic acids like gluconic acid, and make the normally insoluble phosphate compounds available in the root zone to plants. The phosphate solubilization process according to Rodríguez & Fraga (1999).

- **Phytohormone Production:** Many biofertilizers produce plant growth regulators such as auxins, cytokinins, and gibberellins that promote root growth and nutrient uptake (Bashan *et al.,* 2014).
- **Soil Microbial Diversity Enhancement:** Biofertilizers enhance soil fertility by imparting beneficial microorganisms for nutrient cycling, organic matter decomposition, and natural disease suppression (Singh *et al.,* 2020).

2.6 Agronomic and Environmental Benefits

Application of biofertilizers has measurable improvements in crop performance and sustainability at the ecosystems level. They act as reducing agents for chemical fertilizers, therefore saving input costs while controlling the leachability of soil and water due to any contamination. They also support soil biodiversity, increase nutrient-use efficiency, and improve plant resistance to environmental stresses, including drought and salinity (Bhattacharyya & Jha, 2012).

This makes biofertilizers one of the inherent practices in sustainable agriculture and organic farming systems, as well as in urban agriculture and climate-resilient systems.

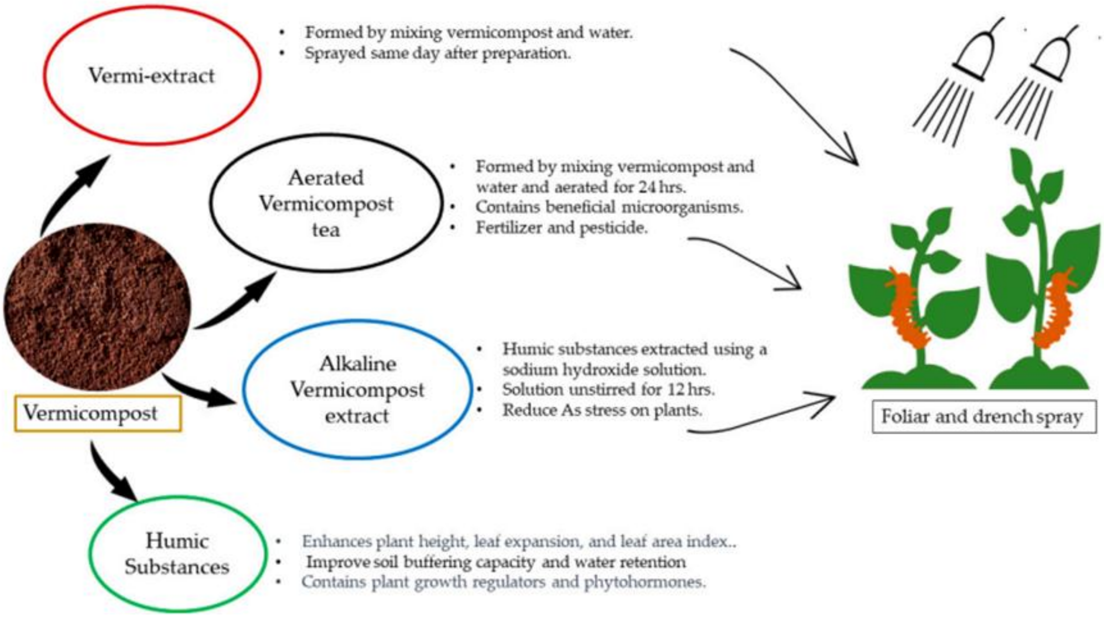

Figure 7: Vermicompost derivative application (Oyege, 2023)

2.7 Limitations and Future Perspectives

A number of issues discourage biofertilizers from becoming popular as a general source. Their overall efficiency also varies with environmental conditions, soil microbial community, and fitness of the organisms upon application. Other constraints that restrict application and accessibility of biofertilizers include short shelf life, vulnerability to storage conditions, and farmers' ignorance.

New developments are focusing on novel formulation techniques, microbial consortia, and biofertilizer with biostimulant integration and digital agriculture technologies. Improved precision application and targeted delivery mechanisms for the optimization of biofertilizer effectiveness in diverse agroecosystems are also being developed (Kumar *et al.,* 2020).

3. Soilless Cultivation and the Nutrient Film Technique (NFT)

3.1 Historical Background and Advantages of Soilless Cultivation

Soilless culture, or hydroponics, is the growing of plants in the absence of soil using a nutrient-rich water solution. The practice became more mainstream since the mid-20th century as a reaction to the increasing demand for more efficient resource utilization and high-yielding cropping.

The Nutrient Film Technique (NFT), the most widely used hydroponic system, was developed in the late 1960s at the Glasshouse Crops Research Institute in the UK (Cooper, 1967; Graves, 1983). It offered a continuous, low-volume system of nutrient delivery that revolutionized hydroponic agriculture.

Hydroponics and NFT systems have the following key benefits:

• water conservation through recycling of nutrients

• lower fertilizer application and environmental runoff

• no pathogen in the soil, hence no chemical fumigation necessary

• maximum use of space, ideal for vertical farming and urban agriculture

• accelerated growth of plants, owing to targeted delivery of oxygen and nutrients to the root zone (Al-Maskri *et al.,* 2010; Hosseini *et al.,* 2021)

3.2 Principles of Hydroponics

In hydroponic systems, a nutrient solution is delivered directly to plant roots under controlled conditions such as oxygen levels, pH, and temperature (Taiz *et al.,* 2015).

Plants may either be supported in inert substrates (such as rock wool, perlite) or left suspended in a nutrient solution where their roots are immersed or exposed. The maintenance of electrical conductivity (EC) and pH (generally 5.5–6.5) suitable for optimum nutrient uptake is crucial (Tüzel *et al.,* 2019; Samba *et al.,* 2023). The result of controlled root environment is uniform plant growth with enhanced productivity and least wastage of resources.

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3.3 The NFT System: Functioning and Applications

NFT refers to the Nutrient Film Technique, which consists of a continuous, shallow stream of nutrient solution flowing across sloped channels with the roots of plants exposed. Through this arrangement, water, nutrients, and oxygen can all be delivered to the roots in one go. The solution is drained by gravity from the reservoir, through the channels, and back to the reservoir, thereby forming a close-loop operation (Burrage, 1999; Rajaseger, 2023).

NFT works best for light-rooted, rapidly growing crops such as lettuce, spinach, and herbs; however, for larger crops, clogging and instability make it unsuitable. It is presently growing into vertical NFT systems for urban farming and aquaponics integration, which merges fish-plant production for sustainable nutrient recycling (Blidariu & Grozea, 2011; Al-Zahrani *et al.,* 2023).

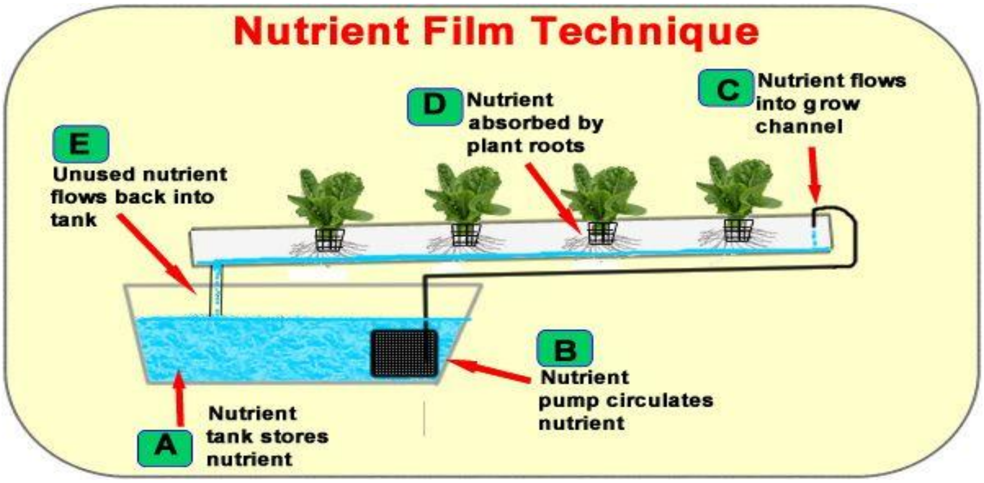

Figure 8: Schematic diagram of an NFT system with recirculating nutrient flow. (anonymous, 2018)

3.4 Nutrient Solution: Formulation, pH, and Ionic Balance

The nutrient solution must provide all essential macro- (N, P, K, Ca, Mg, S) and micronutrients (Fe, Zn, Cu, Mn, B, Mo) in a soluble and bioavailable form for proper plant uptake (Marschner, 2012).

- pH balance of 5.5–6.5 will allow nutrients to be taken up
- EC control helps maintain the proper nutrient strength

- Ionic balance must be maintained to prevent toxicity or deficiency due to nutrient imbalance

Advanced systems continuously monitor the parameters via TDS meters and temperature probes. To prevent accumulation of nutrients, salt stress, or microbial contamination, regular replacement or adjustment is necessary (E3S Web of Conferences, 2024).

3.5 Automation and Parameter Management in Soilless Cultivation

Cotton is one of the crops that is more and more frequently managed automatically to promote crop management in modern NFT systems. Some of the important technologies include:

- IoT-based sensors for monitoring temperature, humidity, light intensity, pH, and nutrient levels.
- Automated dosing systems for nutrient and pH adjustment.
- Data logging platforms for real-time tracking and alerts.
- Backup power supply and pumps, to prevent crop failure and ensure continuity of operations.

The automation provides accuracy while reducing labor and maintaining crop uniformity and yield. In the present day, research is being performed into AI algorithm integrations and predictive systems for proactive control and early detection of system faults (Topalcengiz *et al.,* 2024).

4.Chili Pepper Cultivation (*Capsicum spp.*)

The chili pepper (*Capsicum annuum* L.) is an herbaceous annual plant grown worldwide for its fruits used as vegetables, spice, and medicinal preparations and belongs to the family Solanaceae. The plant grows bushy, with simple leaves arranged alternately and solitary white flowers that develop into fleshy berries. The fruits vary tremendously in their shape, size, and color, and they are nutritionally rich in vitamin C, provitamin A (carotenoids), phenolic compounds, and capsaicinoids, especially capsaicin-the chemical responsible for their pungency. Chili peppers thrive in warm climates with fertile, well-drained soils and show moderate sensitivity to abiotic stressors such as drought and salinity. Further, Capsicum annuum has been established as a model species in sustainable agriculture, especially in studies

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involving organic amendments, biofertilizers, and the plant's response to environmental stresses (Rengasamy *et al.,* 2021; Tait *et al.,* 2022; Pereira-Dias *et al.,* 2023).

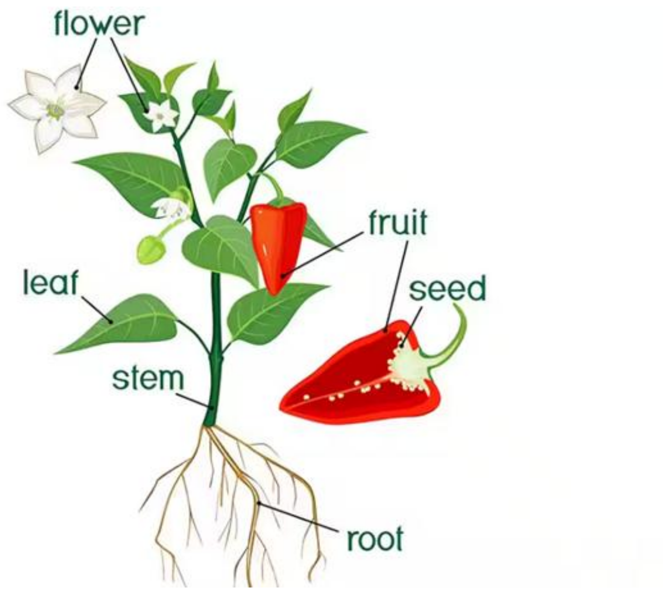

Figure 9: Morphological structure of a chili pepper plant (Drishti Sethi, 2025).

4.1 Origin, Economic Importance, and Botanical Classification

Chili-peppers come from tropical to subtropical environments of Central America and South America. Archaeobotanical findings trace their domestication back to over 7000 years in regions including but not limited to Mexico and Peru (Perry *et al.,* 2007).

The Capsicum genus belongs to the Solanaceae family and comprises approximately 35 species, of which five are widely cultivated: C. annuum, C. frutescens, C. chinense, C. baccatum, and C. pubescens (Bosland & Votava, 2021).

Chili peppers rank among the most lucrative spices globally. In the year 2024, it was valued at about USD 4.8 billion and will rise to USD 7.6 billion in 2033 as a result of the increasing demand from the food, pharmaceutical, and cosmetic industries (Market Research Future, 2023). Leading nations in production include India, China, Mexico, and Spain.

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Botanical classification of Capsicum annuum according to APG IV (2016):

- **Kingdom:** Plantae
- **Clade:** Angiosperms
- **Clade:** Eudicots
- **Order:** Solanales
- **Family:** Solanaceae
- **Genus:** *Capsicum*
- **Species**: *L.*
- **Common names:** Hot pepper, chili pepper, paprika

4.2 Pedoclimatic Requirements for Cultivation

Well-drained, fertile soils rich in organic matter with an optimal pH of 6.0–7.0 are preferred by the chili peppers (FAO, 2022). Good root development is ensured by loamy to sandy loam soils.

The ideal growth temperature lies between 20°C and 30°C. Below 15°C, growth slow; above 35Â°C, fruit quality is affected (Singh *et al.,* 2021). Moderate humidity of 60-70% and moisture in the soil at 80-85% field capacity are required to prevent flower drop. Capsaicin synthesis and overall plant vigor hugely depend on sunlight (Kumar *et al.,* 2020).

4.3 Morphology and Developmental cycle

Chili plants grow to heights ranging from 30 cm to 1.5 m, depending on variety and environment. Leaves are simple, ovate to lanceolate, and arranged alternately. Flowers are axillary, solitary, typically white, with five petals.

The fruits can vary considerably in shape (conical, bell-shaped, or elongated), color (green, red, yellow, or purple), and pungency. Full growth from seed to fruit takes 70-95 days in the life cycle: germination, vegetative growth, flowering, fruit setting, and fruit ripening (Bosland & Votava, 2021).

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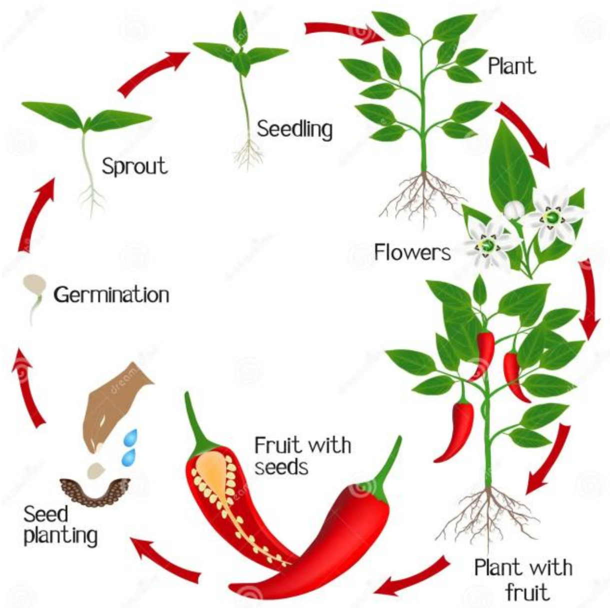

Figure 10: Growth stages of a chili pepper plant (Anonymous, 2025).

4.4 Nutritional Composition and Bioactive Properties

Chili peppers are a rich source of vitamin C, provitamin A, B vitamins, potassium, magnesium, and dietary fiber (Rodriguez *et al.,* 2022). Their dominant bioactive compounds, capsaicinoids (chiefly capsaicin and dihydrocapsaicin), possess antioxidant, anti-inflammatory, and analgesic activities (Szolcsányi, 2021). Flavonoids, phenolic acids, and volatile oils are other significant constituents that contribute to health and flavor.

4.5 Culinary, Medicinal, and Industrial Uses

Culinary: Used globally in fresh, dried, powdered, and processed forms for their flavor, color, and spiciness (FAO, 2022).

Medicinal: Capsaicin patches and creams for the relief of pain (e.g., arthritis, neuropathy). Gastrointestinal and antimicrobial uses have been traditional applications (Szolcsányi, 2021).

Industrial: Capsaicin is applied in medicine, cosmetics, natural dyes, and defense sprays. Its extraction has nutraceutical value (Market Research Future, 2023).

Agronomic: Certain types are grown as ornamental crops or pest-repellent companions in organic farming.

Chapter II: Materials and methods

1. Objective

The plant used for our experiment is pepper (*Capsicum spp*.), due to its economic and culinary importance.

The objective of our study is to evaluate the effects of plant- and organic-based biofertilizers on the vegetative development, growth stimulation, reproduction, and phytosanitary condition of pepper, within a soilless cultivation using the Nutrient Film Technique (NFT).

2. Description of the Experimental Site

The experimental part of this study was carried out in a polycarbonate greenhouse (Figure 11), located at the Department of Biotechnology of Blida 1 University, in the Mitidja plain.

Figure 11: Location of the experiment *(Laboratory of Biotechnology and Plant Production)* (Google Earth, 2025).

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The main characteristics of the greenhouse are:

- Rectangular shape, with an area of 382.5 m².
- North-south orientation.
- Ventilation provided by large side windows on both sides of the greenhouse.
- Heating ensured by hot water radiators.

3. Description of the Experimental Setup

Plant Material:

The plant material used consists of the following species:

✓ **Variety: *Capsicum annuum* F1 Bravo (young pepper plants)**

- **Shape:** Elongated and conical fruits
- **Color:** Shiny red when ripe
- **Texture:** Smooth and firm
- **Flavor:** Mildly sweet and aromatic
- **Growth Habit:** Vigorous plant with high productivity

These plants were provided by a farmer from the Tipaza region. They were thoroughly washed, and only healthy seedlings were selected and placed in pre-drilled pots filled with peat.

Experimental Period:

The experimental period was selected to encompass all phenological stages of the pepper plant, ensuring the development of the maximum number of floral clusters and obtaining a sufficient fruit yield.

The experiment was conducted from **24 February, 2025, to 12 May 2025**.

Setup of the Experimental Device:

The experimental trials were carried out using a system composed of five white PVC pipes, each 80 mm in diameter and 8 meters long, perforated using a drill. The holes, spaced 15 cm apart, hold plastic pots with drainage holes. The pipes were arranged on a table, inclined with the help of wooden beams and secured with fasteners. To control the pressure of the nutrient solution, each end of the pipes was equipped with a valve. The seedlings were placed in beakers with a diameter of 7cm, and a height of 7cm.

Each tube is supplied with the nutrient solution using submersible pumps.

The fertilizers flow throughout the entire length of the tube and return to the reservoirs, creating a closed-loop system. It should be noted that this solution is well oxygenated. (Figures 12 and 13).

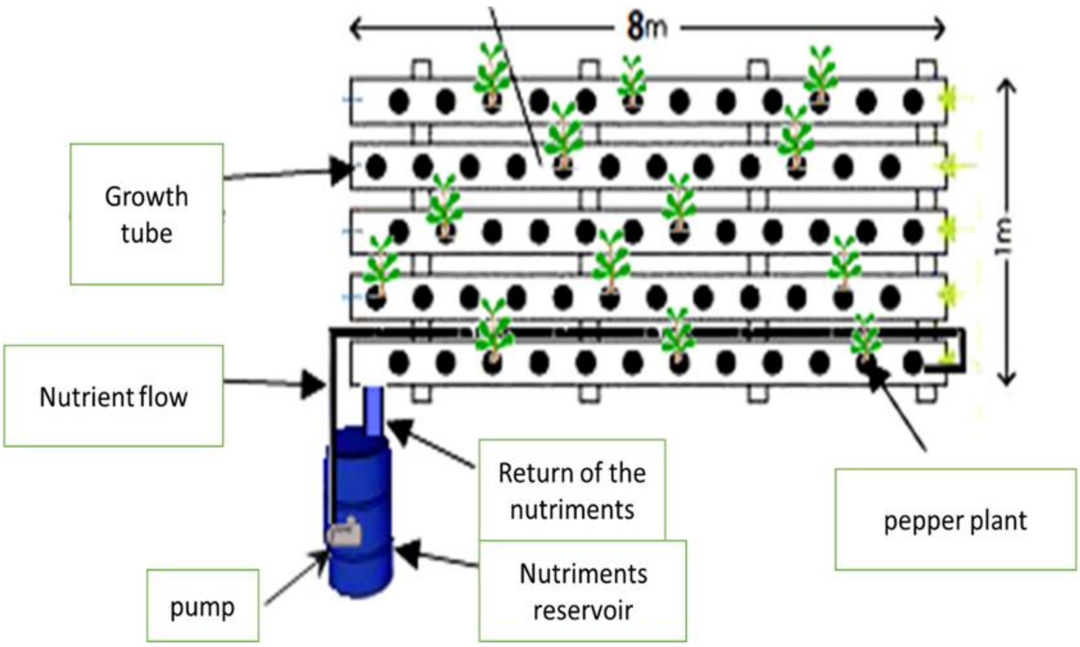

Figure 12: Descriptive diagram of the experimental setup (Birane, 2018).

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Figure 13: Experimental dispositive (Original, 2025)

The acidity (pH) of the solution is measured periodically using a pH meter throughout the experiment.

The trials were conducted in a completely randomized block design, consisting of 5 blocks with 30 plants per treatment, making a total of 150 plants (Figure 13). The treatments were applied as follows:

- Bloc 1 → Solution TM (Control)
- Bloc 2 → Solution MVC (Vermicompost extract)
- Bloc 3 → Solution MI-MUR-F (Millet + vermicompost fermented from mulberry)
- Bloc 4 → Solution MI-PO-F (Millet + vermicompost fermented from poplar)
- Bloc 5 → Solution MI-RATIO-F (Millet + vermicompost fermented from a plant mixture)

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4. Fermented Extract Preparation

A fermentation-based process was used to produce the biofertilizer extract. Vermicompost and powdered plant material were combined, and the mixture was allowed to ferment for 20 days in an incubator. After the fermentation phase, the substrate was mixed with water (v/v), then filtered to remove solid residues and centrifuged at 1500 rpm for 10 minutes. The resulting supernatant (fermented extract) was collected and stored at room temperature in sterile containers for later use.

5. Evaluation of Vegetative Expression

5.1. Estimation of Growth Parameters

5.1.1. Measurement of Aerial and Root Parts

The aerial part was measured in centimeters using a graduated ruler, from the collar (hypocotyl junction) to the apex, for each plant at every sampling time.

The root part was measured by assessing the length of the main root axis, also in centimeters, from the collar down to the root tip, using a graduated ruler.

5.1.2. Estimation of the Number of Expanded Leaves

Manual counting was performed on the aerial part of each plant to determine the number of fully developed leaves.

5.1.3. Estimation of Fresh Weight of Aerial and Root Parts

This involved weighing the aerial and root parts separately in their fresh state, immediately after plant uprooting, using a precision balance.

5.1.4. Estimation of Dry Weight of Aerial and Root Parts

The fresh and dry biomass of both aerial and root systems was assessed. To determine dry weight, the plant material was placed in a ventilated oven at 40 °C for 48 hours. After drying, the biomass was weighed using a precision balance.

5.2. Estimation of Reproductive Parameters

5.2.1. Estimation of the Number of Floral Buds

The number of floral buds was recorded manually by counting them on each plant. Observations were made daily to monitor the initiation and progression of reproductive development.

5.2.2. Estimation of the Number of Flowers

Flower emergence was monitored by counting the number of open flowers on each plant every day. This parameter reflects the plant's flowering capacity under each treatment.

5.2.3. Estimation of the Number of Fruits

Fruits were counted manually once they began to form. Daily observations were conducted to track the fruit set per plant, allowing comparison between treatments.

The principle consisted of manually counting the number of floral buds, flowers, and fruits on each plant daily throughout the experimental period.

5.3. Fresh and Dry Weight of Aerial and Root Parts

The fresh and dry biomass of the aerial and root parts was measured. To determine dry weight, the plant material was placed in a drying oven at 40 °C for 48 hours.

5.4. Length of Roots and Shoots

The lengths of the roots and aerial parts were measured in centimeters using a standard ruler, from the base to the tip of each respective organ.

Figure 14: Measurement of leaf dimensions (length and width) using a ruler (Original, 2025)

6. Evaluation of Physiological Parameters

6.1. Relative Water Content (RWC)

We selected relative water content (RWC) as an indicator of the plant's water status. It expresses the amount of water present in the leaf as a percentage of the amount at full saturation. It is a reliable physiological parameter, similar in function to water potential.

The RWC is calculated using the following formula:

RWC (%) = (FW – DW) × 100 / (TW – DW)

Where:

- FW: Fresh Weight
- TW: Turgid Weight (after full saturation)
- DW: Dry Weight

The fresh weight is determined by weighing the leaf immediately after sampling. The turgid weight is obtained by placing the leaf in distilled water for 24 hours. The dry weight is obtained by drying the leaf in an oven until its weight stabilizes.

6.2. Chlorophyll Content

Chlorophyll content was assessed using a chlorophyll meter by taking readings on the upper surface of healthy, mature leaves throughout the experimental period. The chlorophyll meter determines the relative amount of chlorophyll by measuring the absorbance of the leaf at two specific wavelength regions: red and near-infrared. Based on these absorbance values, the device calculates a numerical SPAD value, which is proportional to the chlorophyll concentration in the leaf (Ling *et al.,* 2011).

Figure 15: Measurement of chlorophyll content using a chlorophyll meter (Original, 2025)

7. statistical analysis

The results were organized and visualized using Microsoft Excel. To evaluate the impact of the different biofertilizer treatments on the overall growth parameters, a Principal Component Analysis (PCA) was performed using the PAST software (version 1.91). This multivariate analysis allowed for the identification of the most significant variables and treatment groups based on their effect on plant growth.

The data were subjected to analysis of variance (ANOVA) using ExcelStat. A comparison of means was then performed using Tukey's test ($p \leq 0.05$), allowing the treatments to be grouped using distinct letters (a, b, ab, etc.) to indicate significant differences among them.

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Chapter III: Results

1. Effects of Bioproducts on Growth Parameters

1.1. Trends in Growth Parameters under the Influence of Bioproducts

The experiment was designed to cover a wide range of growth parameters in order to assess whether the bioproducts applied had a stimulating, inhibiting, or neutral effect on plant development. To better understand the relationship between the measured parameters and the effects of the bioproducts, a Principal Component Analysis (PCA) was performed. This method proved relevant, as the first two principal axes accounted for more than 90% of the total variance (Figure 16).

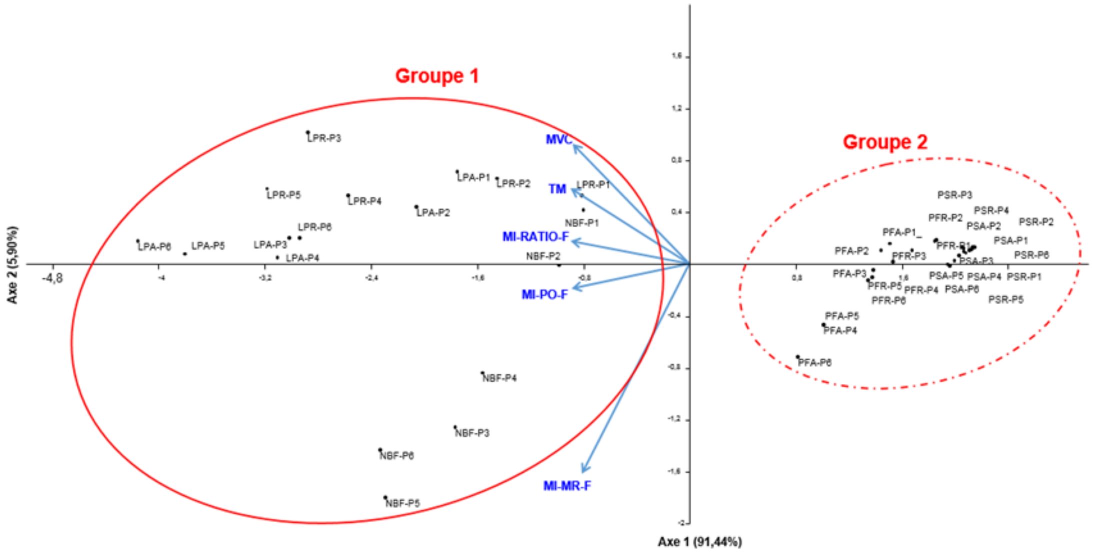

Figure 16: Projection of pepper growth parameters under the influence of bioproducts on the two PCA axes

LPA: Shoot length, LPR: Root length, NBF: Number of leaves, PFA: Fresh weight of the aerial part, PFR: Fresh weight of the roots, PSA: Dry weight of the aerial part, PSR: Dry weight of the roots.

TM: Control, MVC: Vermicompost mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend.

The projection of growth parameters (LPA, LPR, NBF, PFA, PFR, PSA, and PSR) onto the first PCA axis, which explains 91.44% of the variance, reveals the formation of two distinct groups. The first group (Group 1), located on the positive side of the axis, includes variables related to the fresh and dry weights of both aerial and root parts. The second group (Group 2) comprises parameters associated with shoot and root length, as well as the number of leaves. The analysis of vectors representing the bioproducts indicates a positive effect on the second group of variables, while no notable influence was observed on the first group. Therefore, parameters related to fresh and dry weight were not retained for further analysis (Figure 16).

Continuing our approach, we applied the same analysis specifically to the effects of bioproducts on shoot length, root length, and number of leaves in pepper plants. The comparison of these retained parameters based on the bioproduct composition primarily depends on the presence of phytochemical compounds. The projection of values on the first PCA axis, accounting for 57.26% of the variance, highlights a growth-promoting effect of the bioproducts on shoot and root length, observable from the third application. This trend is confirmed by Pearson correlation coefficients (Figure 17), especially for the Vermicompost mixture (MVC) (r = –0.812), Fermented Millet-Poplar (MI-PO-F) (r = –0.810), and Fermented Plant Blend (MI-RATIO-F) (r = –0.820), all of which positively influenced vegetative growth.

On the other hand, analysis of the second axis (26.85% of the variance) shows early and marked vegetative growth starting from the first two applications under the influence of the MVC treatment (r = 0.514). In contrast, the MI-MR-F (r = –0.915) and MI-PO-F (r = –0.399) treatments were associated with delayed vegetative stimulation, observed from the fifth or sixth application (Figure 17).

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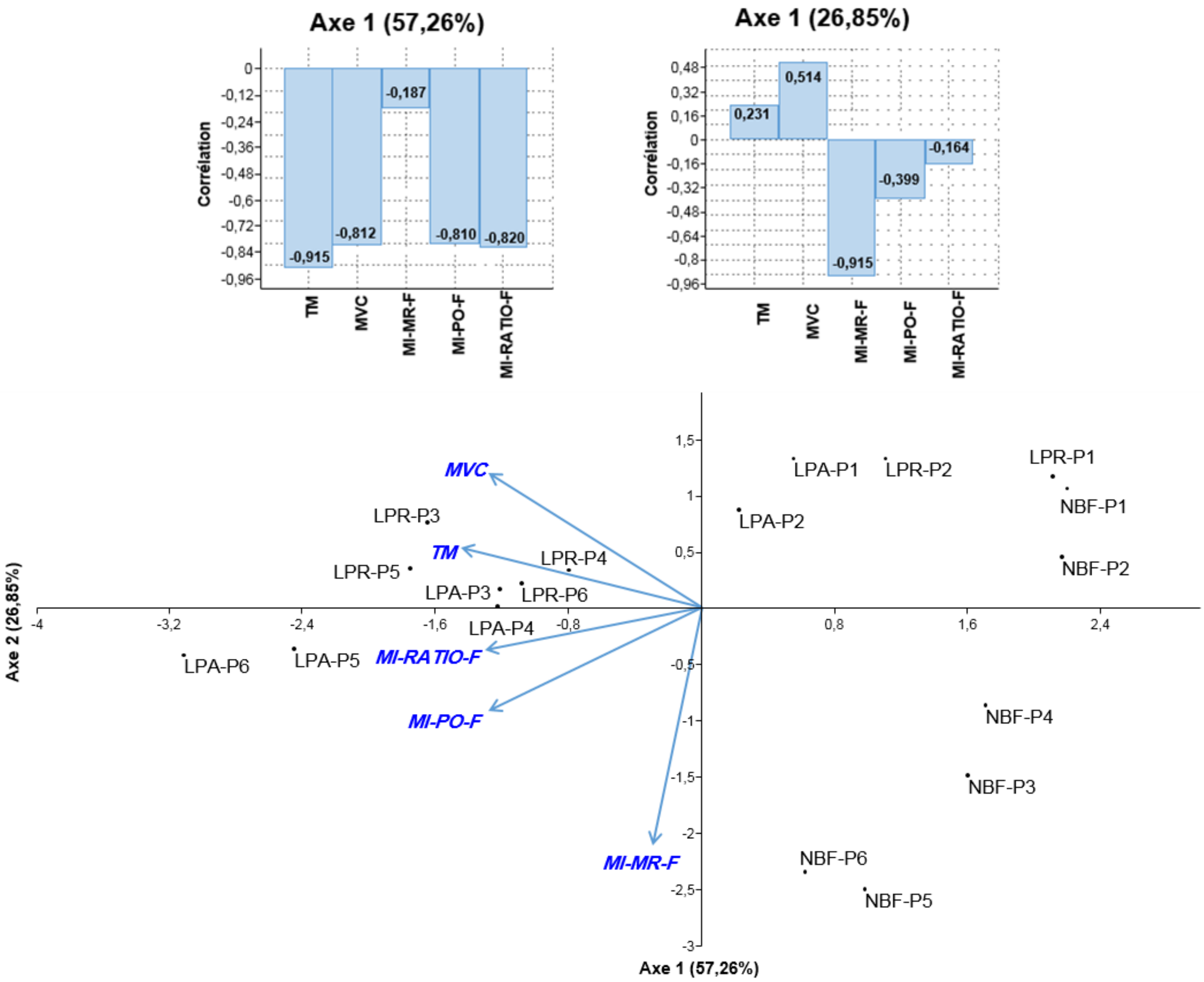

Figure 17: Projection of shoot/root length and number of leaves of pepper plants under the influence of bioproducts on the two PCA axes
LPA: Shoot length, LPR: Root length, NBF: Number of leaves, TM: Control, MVC: Vermicompost mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

1.2. Comparative Study of Growth Parameters under the Influence of Bioproducts

Figures 18a, 18b, and 18c illustrate the variation in growth parameters under the effect of bioproducts. According to the GLM model results, a significant positive variation in growth parameters was observed, indicating a highly significant treatment effect: LPA ($p = 2.45\times10^{-6}$, $p < 0.01\%$), LPR ($p = 1.19\times10^{-7}$, $p < 0.01\%$), NBF ($p = 4.08\times10^{-6}$, $p < 0.01\%$).

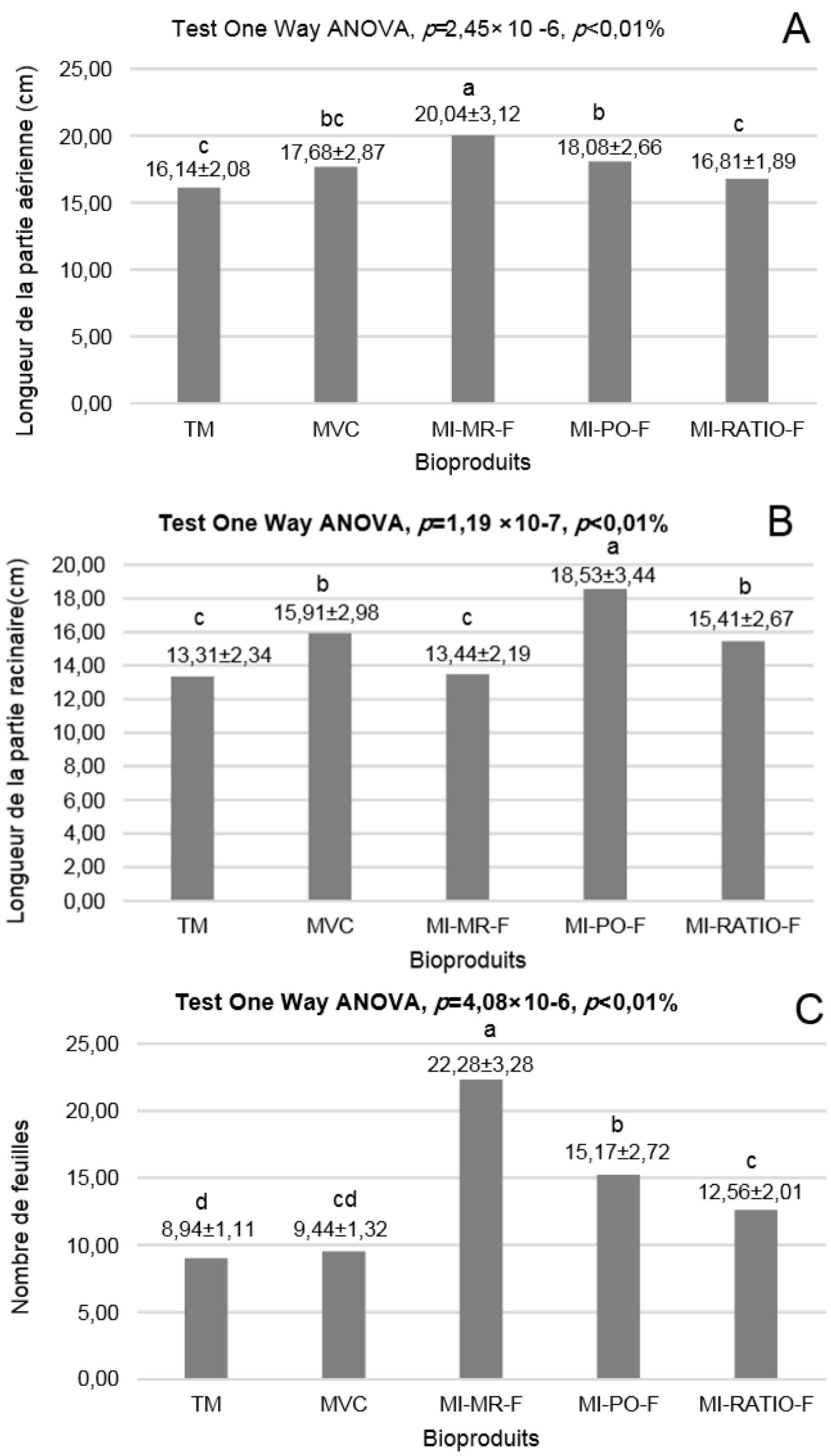

Figure 18: Estimation of bioproduct effects on the growth parameters of pepper plants

TM: Control, MVC: Vermicompost mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

The analysis of shoot length using Tukey's post-hoc test revealed four homogeneous groups. The highest growth was observed under the MI-MR-F treatment (Group a). Intermediate growth was seen in the MI-PO-F (Group b) and MVC (Group bc) treatments. In contrast, the lowest growth was recorded in the control and MI-RATIO-F treatments (Group c) (Figure 18a).

Regarding root length, the same test revealed three statistically distinct groups. MI-PO-F treatment induced the greatest root growth (Group a), followed by moderate growth under MI-RATIO-F and MVC treatments (Group b). The lowest growth was observed in control and MI-MR-F plants (Group c) (Figure 18b).

Tukey's post-hoc test applied to the number of leaves identified five distinct response profiles to the treatments. MI-MR-F showed a significantly higher performance, indicating optimal vegetative leaf production (Group a). MI-PO-F and MI-RATIO-F had moderate effects (Groups b and c, respectively). Conversely, MVC-treated plants showed marginal effects (Group cd), suggesting a limited contribution to leaf proliferation (Figure 18c).

2. Effects of Bioproducts on Production Parameters

2.1. Trends in Production Parameters under the Effect of Treatments

2.1.1. Floral Bud Trends

Principal Component Analysis (PCA) was applied to the pepper floral bud data to identify key patterns associated with bioproduct effects (Figure 19). The first two principal axes accounted for 75.89% of the total variance: 54.72% for Axis 1 and 21.17% for Axis 2.

Along Axis 1, a gradual distribution of treatments is observed, with positive correlations increasing from the Control (TM) (r = 0.105) up to MI-RATIO-F (r = 0.539), passing through MVC (r = 0.482), MI-MR-F (r = 0.427), and MI-PO-F (r = 0.531). This indicates a generally stimulating effect of bioproducts on flowering, with varying intensity depending on their composition. Although the control is also located in the positive zone, its weak correlation suggests minimal stimulation in the absence of organic treatment.

Axis 2 (21.17% of the variance) adds a temporal dimension to the interpretation. The MI-MR-F method (r = 0.320) shows a stronger correlation here, indicating a relatively early response. MI-PO-F (r = 0.271) follows a similar trend. In contrast, MVC presents a negative value (r = –0.365), indicating a later onset of flowering. MI-RATIO-F, located near the origin (r = –0.032), suggests a more stable or evenly distributed response over time.

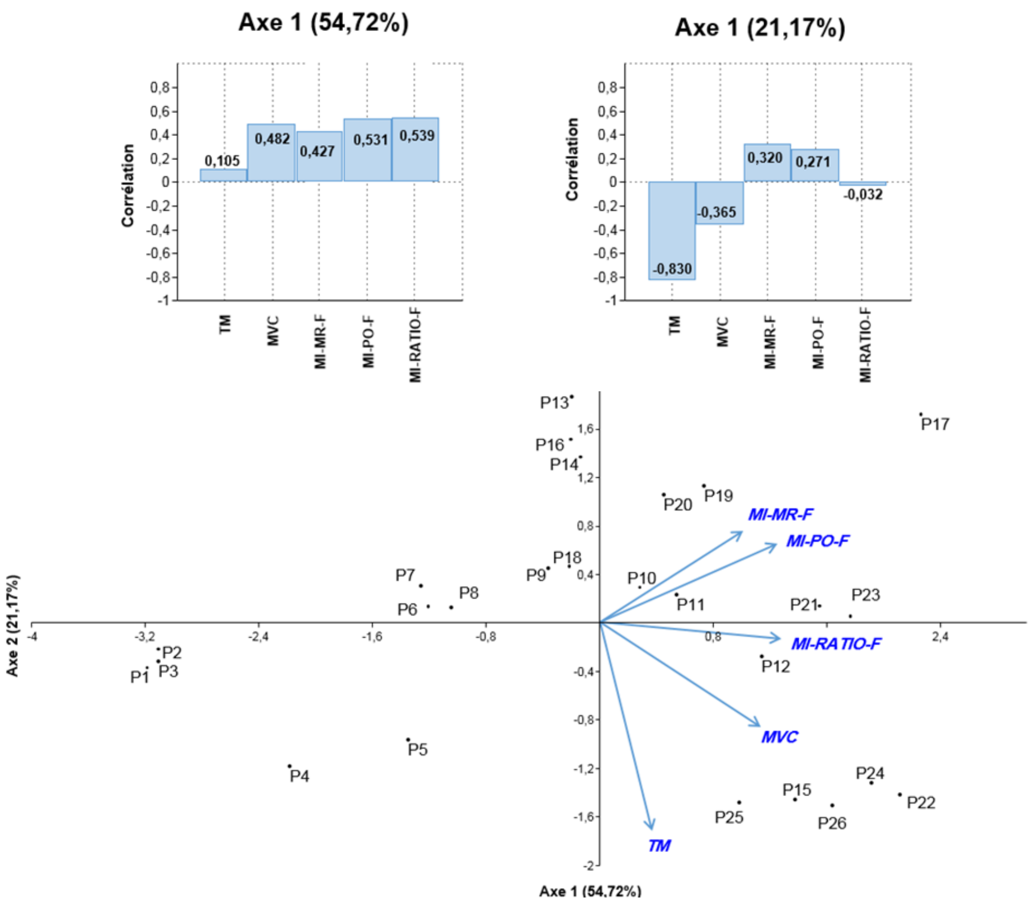

Figure 19: Projection of pepper floral buds under the effect of bioproducts on the two PCA axes

TM: Control, MVC: Vermicompost Mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

2.1.2. Flowering Trends

PCA applied to flower data shows the differential impact of bioproducts on this parameter (Figure 20). The first two axes explain 69.26% of total variance: 47.95% for Axis 1 and 21.31% for Axis 2.

Axis 1 highlights a clear separation between the control (TM), located in the positive zone (r = 0.157), and all other treatments, which show negative correlations: MI-MR-F (r = –0.561), MI-RATIO-F (r = –0.540), MI-PO-F (r = –0.492), and MVC (r = –0.354). This distribution reflects the structuring effect of bioproducts on flowering, where a more negative correlation suggests a stronger impact compared to the untreated control.

Axis 2 shows variation among bioproducts. MVC stands out with a strong positive correlation (r = 0.724), indicating significant influence on another aspect of flowering dynamics. TM (r = 0.322) and MI-RATIO-F (r = 0.307) also show moderate positive correlations. In contrast, MI-MR-F (r = –0.264) and MI-PO-F (r = –0.454) exhibit negative correlations, suggesting a more specific or delayed flowering response.

These findings imply that the bioproducts have contrasting effects on flowering: MVC promotes active floral development, while MI-MR-F and MI-PO-F elicit more moderate or delayed responses. Although the control shows positive correlations, its influence remains lower compared to the treated groups.

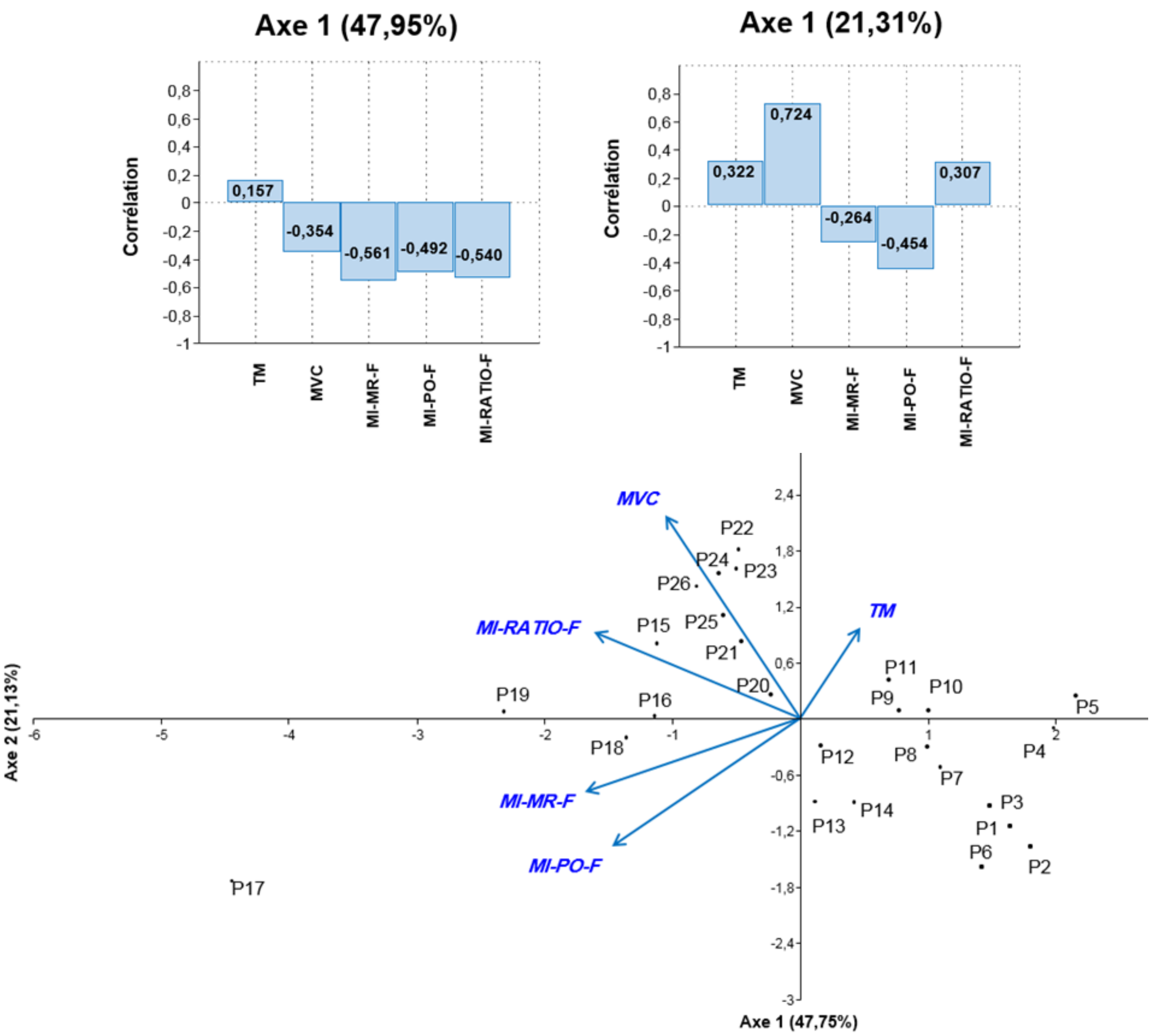

Figure 20: Projection of pepper flowers under the effect of bioproducts on the two PCA axes

TM: Control, MVC: Vermicompost Mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

2.1.3. Fruit Trends

PCA of fruit production data highlights the differing effects of bioproducts on fruit yield in pepper (Figure 21). The first two axes explain a total of 84.83% of the variance: 64.88% for Axis 1 and 19.95% for Axis 2.

All bioproduct treatments show positive correlations along Axis 1, indicating a generally stimulating effect on fruiting. The highest correlations were seen with MI-MR-F (r = 0.535), MI-PO-F (r = 0.532), and MVC (r = 0.497), suggesting significantly improved productivity due to these interventions. MI-RATIO-F also shows a positive correlation (r = 0.420), though slightly lower. The control (TM), with a much lower correlation (r = 0.084), indicates limited fruit production without bioproduct input.

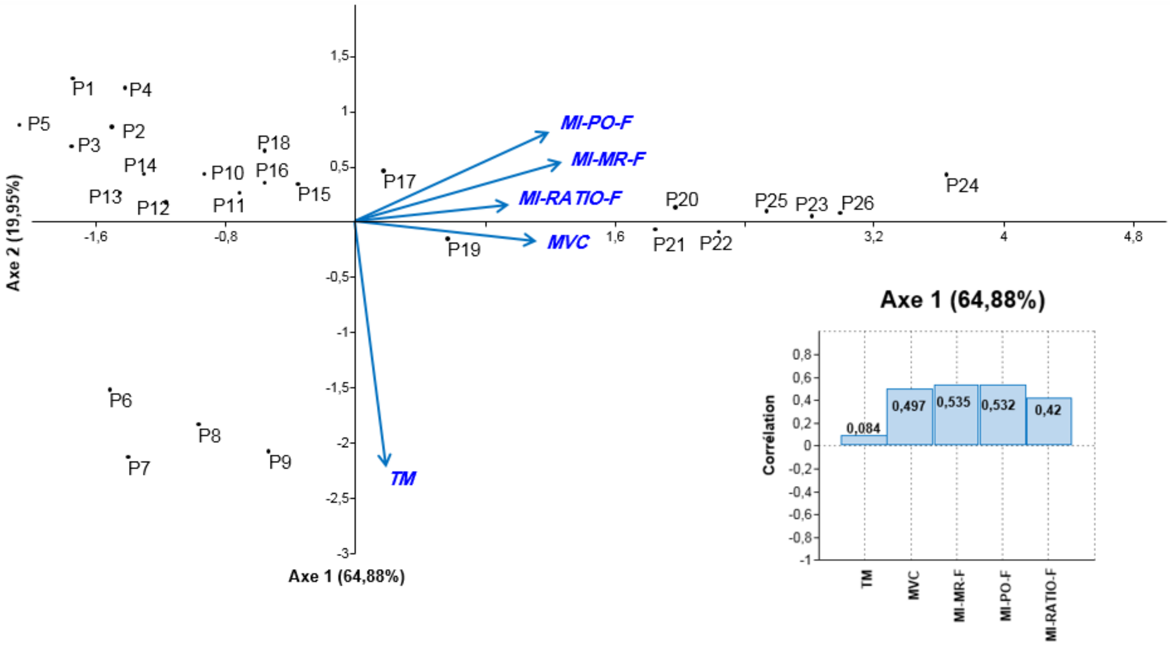

Figure 21: Projection of pepper fruits under the effect of bioproducts on the two PCA axes

TM: Control, MVC: Vermicompost Mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

2.2. Comparative Analysis of Production Parameters under the Effect of Bioproducts

Figures 22a, 22b, and 22c illustrate the variation in production parameters under the influence of bioproducts. Based on the GLM model, the positive variation across parameters confirms a highly significant treatment effect:

Floral buds ($p = 0.012$, $p < 5\%$)

Flowers ($p = 2.74\times10^{-4}$, $p < 0.1\%$)

Fruits ($p = 6.56\times10^{-5}$, $p < 0.1\%$).

Analysis of floral bud production using Tukey's post-hoc test revealed five distinct homogeneous groups (Figure 22a). Group (a), with the highest values, corresponds to MI-MR-F, indicating strong floral induction. Intermediate values were recorded under MI-PO-F and MI-RATIO-F, falling into groups (b) and (c), respectively. The lowest values were observed in MVC-treated plants (group d) and the control (group e), reflecting weak initial flowering stimulation.

Flower number analysis identified three homogeneous groups (Figure 22b). MI-MR-F again stood out with abundant flowering (group a). MVC and MI-PO-F showed moderate effects, grouped as (b) and (c), while MI-RATIO-F shared similar results (group c). The control, with the lowest value, belonged to group (d), indicating minimal flowering without treatment.

Regarding fruit production, the post-hoc test revealed four statistical groups (Figure 22c). MI-MR-F was in group (a), confirming high productivity. MVC and MI-PO-F had similar values and were grouped as (b). The control was placed in group (c), indicating limited fruiting. MI-RATIO-F had the lowest values, placed in group (d), suggesting negligible effect on fruit production.

Overall, these results confirm that MI-MR-F exerts a significantly positive effect on all production parameters, followed by MI-PO-F and MVC with intermediate effects. The control and MI-RATIO-F lag behind with considerably lower performances across all traits.

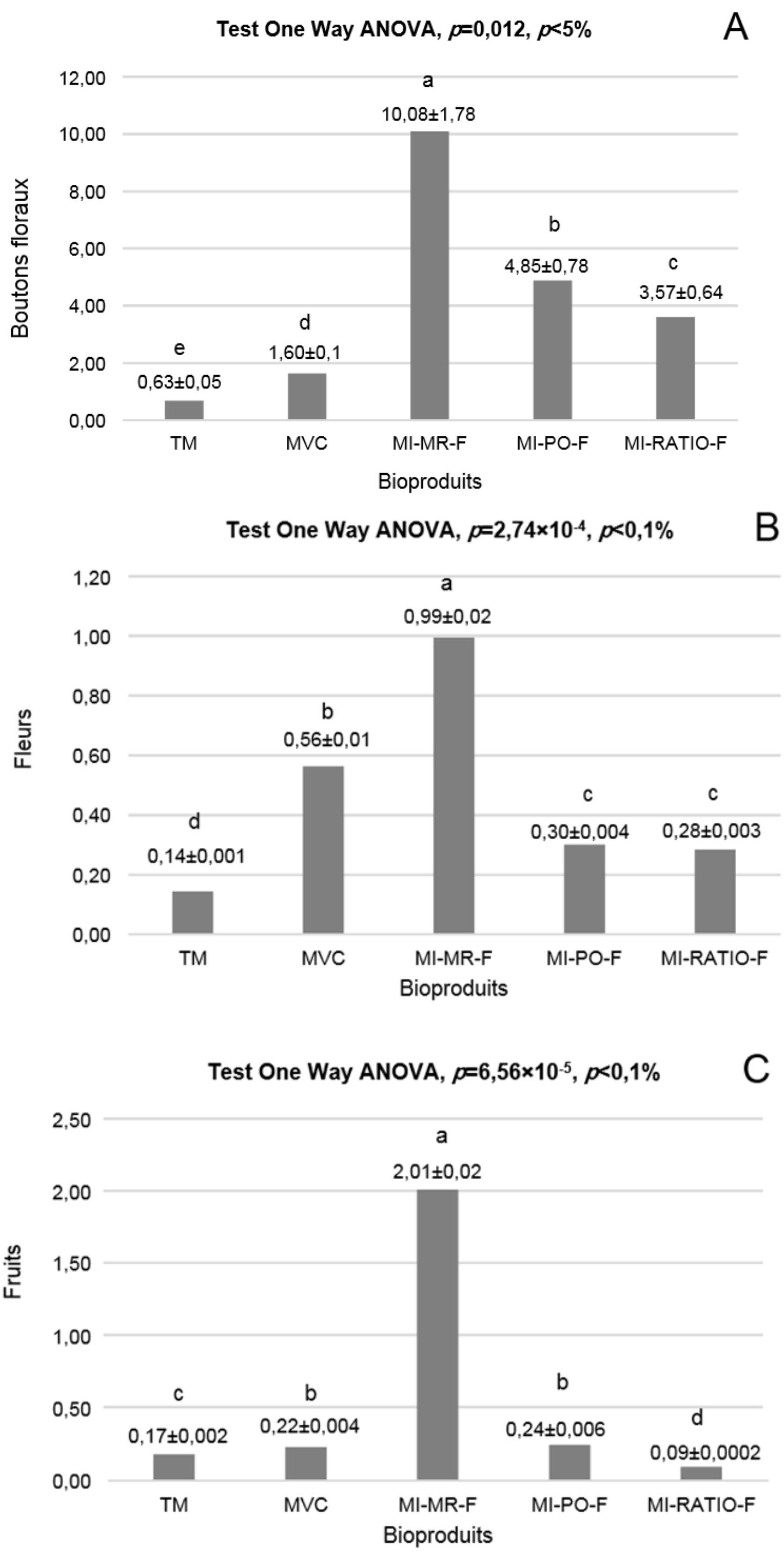

Figure 22: Estimation of bioproduct effects on pepper production parameters
TM: Control, MVC: Vermicompost Mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

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3. Effects of Bioproducts on Physiological Parameters

3.1. Trends in Physiological Parameters under the Effect of Treatments

Principal Component Analysis (PCA) applied to the physiological parameters of pepper reveals a distinct dynamic between chlorophyll accumulation (CH) and relative water content (RWC) under the influence of the bioproducts (Figure 23). The first two principal axes together explain 64.14% of the total variance: 35.58% for Axis 1 and 28.56% for Axis 2, reflecting a moderately satisfactory representation of the dataset.

The projection along Axis 1 shows an early chlorophyll response. This trend is particularly marked in the treatments MVC-CH and MI-MR-F-CH, suggesting a rapid stimulation of chlorophyll biosynthesis during the early growth phases.

In contrast, Axis 2 highlights a later improvement in relative water content. The MVC-RWC and MI-RATIO-F-RWC treatments show high projections on this axis, indicating a progressive enhancement of water adaptation mechanisms in the treated plants.

This physiological sequence—marked first by early chlorophyll activation, followed by delayed stimulation of water content—suggests that the bioproducts primarily act on the plant's energy metabolism before enhancing its water retention and resilience capacity.

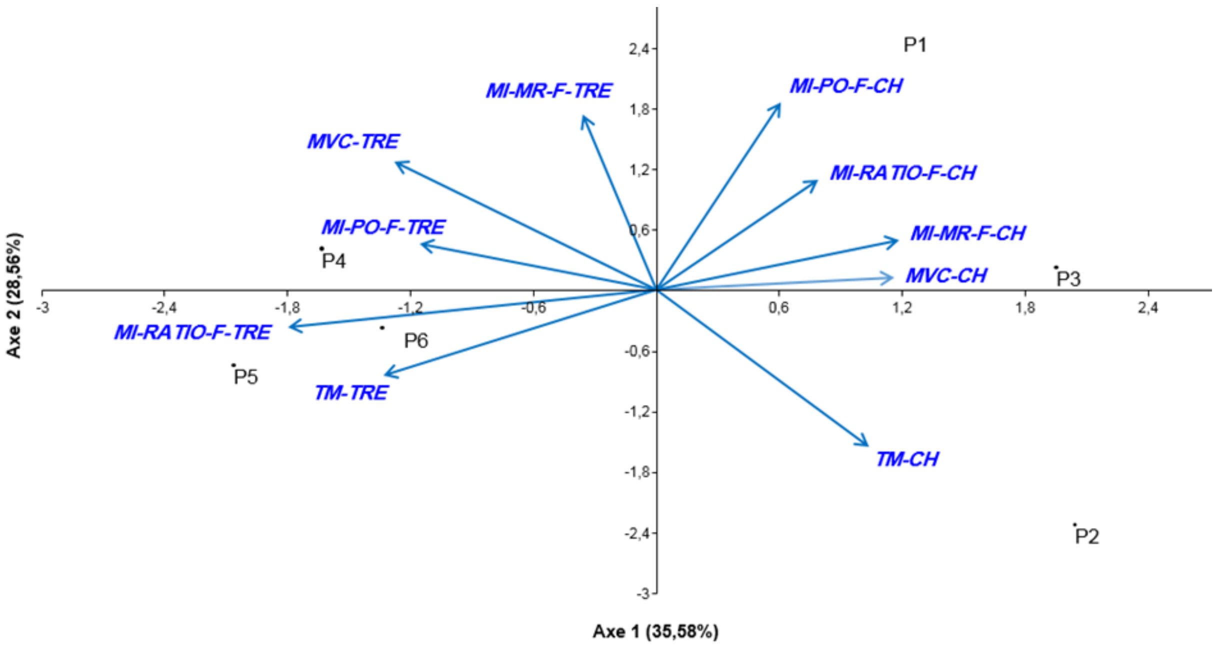

Figure 23: Projection of physiological parameters of pepper under the effect of bioproducts on the two PCA axes

TM: Control, MVC: Vermicompost Mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend.

RWC: Relative Water Content, CH: Chlorophyll

3.2. Comparative Study of Physiological Parameters under the Effect of Bioproducts

Figure 24 illustrates the variation in pepper's physiological parameters under the effect of the bioproducts. According to the ANOVA model results, the variation in chlorophyll (CH) and relative water content (RWC) shows a highly significant difference based on the treatment factor, with the following p-values: chlorophyll ($p = 8.22 \times 10^{-7}$, $p < 0.01\%$) and RWC ($p = 1.11 \times 10^{-4}$, $p < 0.1\%$).

Tukey's post-hoc test revealed the formation of three statistically distinct groups for chlorophyll content. Group (a), which had the highest values, included MVC and MI-PO-F treatments, indicating a strong stimulation of chlorophyll biosynthesis. Group (b) included MI-MR-F and MI-RATIO-F, showing intermediate levels. In contrast, the control (TM) had the lowest chlorophyll accumulation and formed its own group (c), reflecting limited biosynthesis in the absence of bioproducts.

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For relative water content (Figure 24B), the same test revealed four distinct groups. The MI-PO-F treatment alone formed group (a), indicating superior water retention performance. MVC and MI-MR-F were grouped in group (b), indicating moderate improvement in water-holding capacity. MI-RATIO-F was placed in group (c), while the control (TM) occupied group (d), confirming poor water retention without treatment.

These results highlight variable impacts depending on the parameter. MI-PO-F stands out for its dual optimal performance, ranking in group (a) for both variables. MVC and MI-MR-F show consistent, moderate responses, falling into the upper groups for both parameters. MI-RATIO-F had a notable effect on chlorophyll but limited impact on RWC. The control consistently appeared in the lowest-performing groups, confirming poor physiological performance in untreated plants.

This organization highlights the agronomic importance of fermented bioproducts—particularly MI-PO-F—for the general optimization of pepper's physiological functioning.

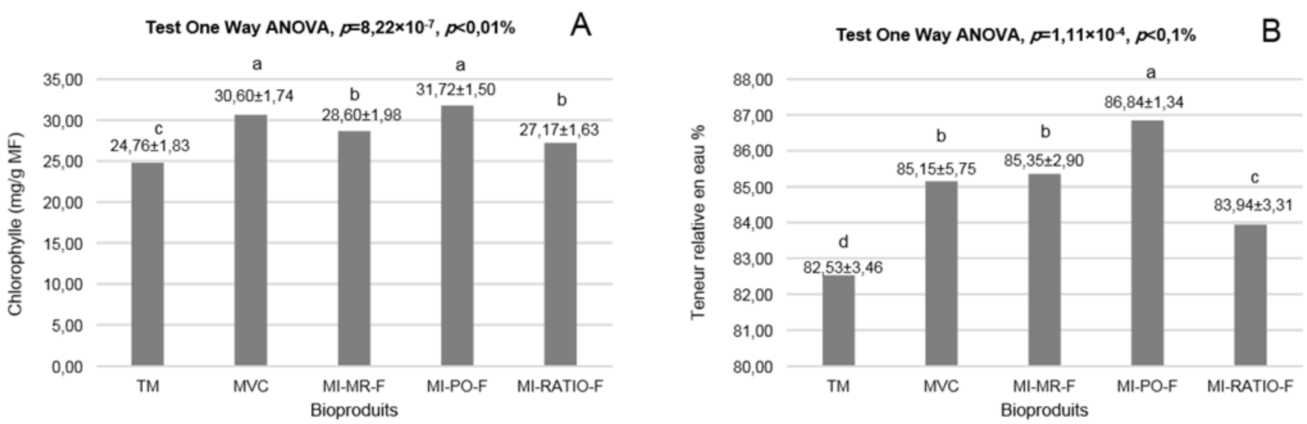

Figure 24: Estimation of the effects of bioproducts on the physiological parameters of pepper

TM: Control, MVC: Vermicompost Mixture, MI-MR-F: Fermented Millet-Mulberry, MI-PO-F: Fermented Millet-Poplar, MI-RATIO-F: Fermented Plant Blend

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Chapiter IV: Discussion

As environmental and health concerns continue to rise, the need for more sustainable farming practices becomes harder to ignore. Among the possible solutions, biofertilizers made from organic matter especially fermented vermicompost products stand out as a natural and promising alternative. While synthetic fertilizers may bring fast results, they often harm soil health over time by causing nutrient runoff, disturbing microbial life, and reducing long-term fertility.

In this study, we explored how different mixtures of fermented bioproducts affected the growth, productivity, and physiological responses of hot pepper (Capsicum annuum L.). The results showed clear differences between treatments, depending on the measured traits. MI-MR-F was especially effective at promoting shoot growth and increasing leaf number, whereas MI-PO-F was more beneficial to root development. These outcomes likely reflect the specific makeup of each mixture including humic substances, microbes, and bioavailable nutrients that interact with the plant in unique ways. Other researchers have also observed similar effects with vermicompost, noting its ability to improve growth through nutrient cycling and microbial stimulation (Atiyeh *et al.,* 2002; Arancon *et al.,* 2004; Bachman & Metzger, 2008; Sinha et al., 2011).

MI-MR-F enhanced aerial growth including shoot elongation, leaf development, flowering, and fruit production. MI-PO-F was most effective at promoting root development. Control plants (TM) showed minimal growth responses.

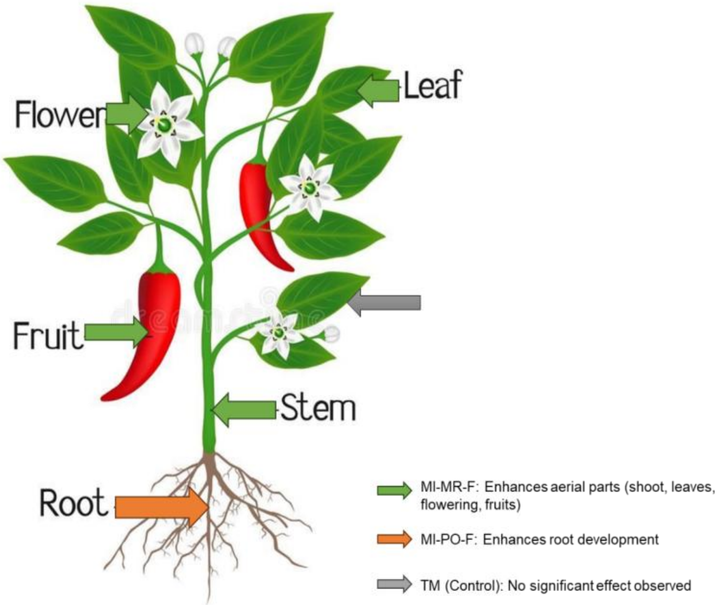

Figure 25: Schematic representation of the effects of different bioproduct treatments on hot pepper *(Capsicum annuum* L.) development. (original,2025)

In terms of flowering and fruiting, MI-MR-F once again gave the strongest results, likely due to natural growth regulators like auxins and gibberellins formed during fermentation. These compounds are known to encourage floral initiation and fruit set (Singh *et al.,* 2008; Suthar, 2010). On the flip side, MI-RATIO-F didn't perform as well in this area, which may point to an unbalanced formulation or a lack of certain key elements.

Physiologically, MI-PO-F showed clear advantages, especially in chlorophyll content and relative water retention. These traits point to better photosynthesis and internal water management. This echoes what Uma and Malathi (2009) observed in their work on vermicompost, where chlorophyll increased noticeably after treatment. The presence of antioxidants and important minerals like potassium and magnesium may be behind these effects (Pant *et al.,* 2012).

Table 1. Symbol-based summary of treatment effects on key plant traits in *Capsicum annuum* L. (original, 2025)

Treatment	Vegetative growth	Reproductive Performance	Physiological Traits
TM	-	-	-
MVC	++	+	++
MI-MR-F	+++	+++	++
MI-PO-F	++(roots)	++	+++
MI-RATIO-F	+	-	++

MI-MR-F showed strong performance in vegetative and reproductive parameters, while MI-PO-F stood out for its effect on root development and physiological responses. Control (TM) showed no significant response across all categories.

Taking all the data into account, it seems that fermented bioproducts particularly MI-MR-F and MI-PO-F hold strong potential for improving crop performance in a natural way. Our findings line up with those of Gopinath *et al.* (2009), who reported that organic amendments can support both yield and plant health. Of course, effectiveness depends on how the products are made and used. The type of organic material, how it's fermented, and how the microbes behave all matter.

Looking forward, it would be useful to test these bioproducts in field conditions and on different crops. This could help define how they might be used at larger scales to support eco-friendly and productive agriculture.

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General conclusion

This study was conducted to evaluate the effects of fermented vermicompost-based bioproducts on the vegetative development, reproductive traits, and physiological status of pepper (*Capsicum spp*.), a crop known for its economic and culinary value. The experiment was carried out using a soilless cultivation system based on the Nutrient Film Technique (NFT) over a period of approximately two and a half months, from late February to mid-May 2025, at the University of Blida.

The results highlighted that the different treatments had varying effects depending on the parameters observed. The MI-MR-F treatment stood out for promoting significant vegetative growth (shoot length, number of leaves) as well as improved flowering and fruit production. The MI-PO-F treatment, on the other hand, showed a notable impact on root development and physiological traits, particularly leaf chlorophyll content and water retention within plant tissues.

From a physiological perspective, the bioproducts tested in this study showed the ability to enhance key functions such as photosynthesis. These effects likely result from the presence of bioactive compounds naturally found in fermented vermicompost, including humic acids, enzymes, and beneficial microorganisms.

Overall, this study supports the potential of fermented organic liquid fertilizers as sustainable alternatives to chemical inputs, especially in water-efficient hydroponic systems. Future research would be useful to better understand the biochemical mechanisms behind their effects and to explore their application in different crops or growing conditions, including open-field systems, greenhouses, or under abiotic stress.

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Master II – Natural and Life Sciences

Specialty: Phytopharmacy and Plant Protection

Stimulatory Effects of Some Organic Fertilizers on Chili Pepper

Presented by :

BELLAH Nedjla Rawane

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