UNIVERSITÀ CATTOLICA DEL SACRO CUORE

Sede di Piacenza

Dottorato di ricerca per il Sistema Agro-alimentare

Ph.D. in Agro-Food System

Cycle XXXVIII

S.S.D. AGRI-02/A

Nutritive profiles of selected leafy vegetables grown on enriched soilless growing media

Coordinator:

Prof. Paolo Ajmone Marsan

Candidate:

Roseline Chemutai

Matriculation n: 5215427

Academic Year 2024/2025

UNIVERSITÀ CATTOLICA DEL SACRO CUORE

Sede di Piacenza

Dottorato di ricerca per il Sistema Agro-alimentare

Ph.D. in Agro-Food System

Cycle XXXVIII

S.S.D. AGRI-02/A

Nutritive profiles of selected leafy vegetables grown on enriched soilless growing media

Coordinator:

Prof. Paolo Ajmone Marsan

Tutor:

Prof. Vincenzo Tabaglio

Candidate:

Roseline Chemutai

Matriculation n: 5215427

Academic Year 2024/2025

Declaration

I, **Roseline Chemutai**, declare that this thesis titled *"Nutritive profiles of selected leafy vegetables grown on enriched soilless growing media"* is my original work and has not been submitted for the award of a degree or diploma in any other university or institution of higher learning. Where other people's work has been used, it has been duly acknowledged.

Signature: ______________________

Date: ___________________________

Approval

This thesis has been submitted with the approval and endorsement of the undersigned supervisor:

Supervisor's Name: Professor Vincenzo Tabaglio

Position: Associate Professor, Department of Sustainable Crop Production

Institution: Università Cattolica del Sacro Cuore

Signature: ___________________________

Date: _______________________________

Acknowledgments

First and foremost, I offer my deepest gratitude to the Almighty God for granting me strength, wisdom, and perseverance throughout the duration of this study.

I extend special appreciation to the Coordinator of the Project, Professor Paolo Ajmone Marson, whose leadership and support provided the foundation for my doctoral journey. I am equally indebted to the PhD School in Agro-Food System (Agri-system) at Università Cattolica del Sacro Cuore, for offering a supportive academic environment and essential resources that made this study possible. My sincere thanks also go to all tutors and staff at Università Cattolica, whose teaching and mentorship enriched my academic growth.

I am profoundly grateful to my supervisor, Professor Vincenzo Tabaglio, for his unwavering guidance, insightful feedback, and continuous encouragement. His mentorship has been invaluable and instrumental to the success of this research.

I gratefully acknowledge the Uganda Martyrs University, Uganda, for the collaboration and support, and the animal nutrition laboratory staff at Makerere University for their technical assistance with laboratory analyses, which was crucial to the completion of this work. I also wish to express my heartfelt appreciation to the Principal of Bukalasa Agricultural College for the institutional support and encouragement extended during the study.

To my fellow African PhD students, I express heartfelt appreciation for the camaraderie, shared experiences, and encouragement that made this journey more meaningful.

To my family and friends, I extend my deepest thanks for your patience, prayers, and moral support. Your belief in me has been a constant source of motivation.

Finally, I acknowledge the many researchers and colleagues who generously shared their knowledge and experiences, enriching the practical relevance of this study.

Abstract

This thesis investigated the nutritive profiles of leafy vegetables cultivated on enriched soilless potting growth media under greenhouse conditions, focusing on spinach (*Spinacia oleracea L.),* cowpea *(Vigna unguiculata L*. Walp.), amaranth (*Amaranthus viridis L*.), and collard *(Brassica oleracea L.).* Three substrate ratios of charcoal dust to coffee husk (2:1, 1:1, 1:2) were combined with three fertilizer treatments *Tithonia diversifolia* leaf powder, inorganic NPK (15:15:15), and an unfertilized control to evaluate morphological traits, yield and nutrient composition (protein, carbohydrate, fibre, ash, fat, dry matter, and iron). Fertilizer regimes significantly influenced nutrient profiles: inorganic inputs enhanced protein *(p= 0.00514*) and fibre *(p= 0.0372)*, while organic amendments promoted carbohydrate *(p= 0.0319)* and iron accumulation. Growth media composition also affected plant responses, with amaranth and collard benefiting most from tailored blends, whereas spinach and cowpea showed resilience across treatments. Cowpea's adaptability was evident in stable dry matter and consistently high protein, reflecting its nitrogen-fixing capacity. Nutrient outcomes were shaped by both fertilizer type and media composition, highlighting interaction effects. However, ANOVA revealed that growth media, fertilizer treatments, and their interaction did not significantly affect yield *(p > 0.05),* with species differences accounting for most variation. Overall, the results show that differences in growth media and fertilizer had no significant impact *(p >0.05)* on dry matter, crude fat, and total ash content, suggesting these traits may be more strongly influenced by genetic variability, environmental conditions, or nutrient interactions. Comparative analysis indicated that soilless systems generally produced higher protein, fibre, and dry matter, while soil-based cultivation yielded greater iron and carbohydrate. In conclusion, integrating waste-derived soilless media with tailored fertilizer regimes offers a scalable and sustainable pathway for leafy vegetable production, with relevance not only for Uganda but also for regions worldwide confronting resource constraints. By advancing resource-efficient cultivation, enriched soilless systems can contribute to global food security and climate-resilient agriculture**.**

Keywords: Soilless cultivation, Tithonia leaf powder, charcoal dust, coffee husk, leafy vegetables, nutritional quality, Uganda.

TABLE OF CONTENTS

List of tables

List of figures

CHAPTER 1: INTRODUCTION

1.0 Introduction

Agricultural production in Uganda plays a central role in food security, livelihoods, and economic development. Among the various crops cultivated, leafy vegetables are vital for their nutritional value, affordability, and cultural significance in local diets. However, the productivity and quality of these vegetables are increasingly threatened by declining soil fertility, erratic weather patterns, and unsustainable farming practices, including the excessive use of chemical fertilizers and pesticides. In response to these challenges, there is growing interest in alternative cultivation systems that promote sustainability, resource efficiency, and nutritional improvement. Soilless agriculture, particularly the use of organic waste materials such as charcoal dust and coffee husk, offers a promising solution for improving vegetable production without relying on conventional soil-based methods. Likewise, the use of organic fertilizers derived from readily available *Tithonia diversifolia* leaves offers an eco-friendly alternative to synthetic inputs, providing potential benefits for crop health and environmental sustainability. This study investigates the combined effects of fertilizer regimes and soilless media compositions on the morphological traits and nutrient profiles of selected leafy vegetables, namely spinach, cowpea, amaranth, and collard. By comparing different media ratios and fertilizer types under controlled greenhouse conditions, the research aims to identify optimal combinations that enhance both yield and nutritional quality. Additionally, a comparative analysis with soil-grown counterparts provides a broader context and benchmark for evaluating the performance of soilless systems.

The chapter proceeds with a detailed background to the study, a statement of the problem, research objectives, hypotheses, and the significance of the study within Uganda's agrifood context.

1.1 Background of the agri-food system in Uganda

Uganda's agrifood system is the cornerstone of its economy, employing approximately two-thirds of the labour force and contributing about one-quarter of the national GDP (Diao et al., 2023; World Bank, 2018). The sector is dominated by smallholder farmers, who account for over 80% of the farming population (Environmental Defenders, 2021). These farmers cultivate a mix of staple crops, cash crops, and horticultural produce, often on plots averaging less than two hectares. Despite favourable agro-ecological conditions, including fertile soils and a generally conducive climate, the country continues to grapple with persistent food insecurity and malnutrition, particularly in rural areas (Galema et al., 2024).

The agrifood system in Uganda is undergoing a gradual transformation, moving from subsistence-oriented production towards more market-integrated and diversified value chains (Diao et al., 2023). However, this transition is uneven, with productivity growth lagging behind population growth, leading to pressure on food supply and rural livelihoods. The heavy reliance on rain-fed agriculture makes the sector highly vulnerable to climate variability, which in turn affects yields, incomes, and food availability (World Bank, 2018).

Vegetables and other horticultural crops present a significant opportunity within Uganda's agrifood system. They are nutrient-dense, have short production cycles, and can be cultivated on small plots, making them ideal for resource-constrained households (Food Systems Profile - Uganda, 2023). Increased vegetable production and consumption have been linked to improved micronutrient intake, especially among women and children (Ayenew et al., 2018). Yet, vegetable farming remains under-prioritized compared to staple crops such as maize and cassava, partly due to limited access to inputs, inadequate extension services, and underdeveloped market infrastructure (FAO, 2024).

Policy frameworks, such as Uganda's Vision 2040 (Government of Uganda, 2013) and the National Development Plan III, (National Planning Authority, 2020) recognize agriculture as a key driver of socio-economic transformation. However, implementation challenges persist, including insufficient investment in rural infrastructure, limited access to affordable credit, and gaps in food safety and quality assurance systems (FAO, 2024). Fertilizer use remains low, and recommendations are often generic rather than tailored to specific agro-ecological zones, resulting in inefficient nutrient use and suboptimal crop performance (AGRA, 2018).

The broader agrifood system also encompasses post-harvest handling, processing, distribution, and retail, all of which are critical for value addition and employment creation. As urbanization accelerates, demand for diverse, safe, and nutritious foods is expected to increase, creating opportunities for agrifood system actors beyond primary production (Diao et al., 2023). However, without targeted interventions to address productivity constraints, climate risks, and market access barriers, Uganda's agrifood system may struggle to meet the nutritional and economic needs of its growing population.

1.1.1 Role of leafy vegetables in Uganda's agrifood system

Table 1: Different uses of leafy vegetables

Key Dimension	Contributions to Agri-Food System
Nutritional Security	Provision of micronutrients (e.g., vitamins A and C, iron, calcium) via intercropped leafy greens; reduction in anemia for women (Kabunga et al., 2014; Rubaihayo, 2002).
Economic Viability	Income from surpluses in home gardens; alignment with market preferences for species like amaranthus and kales (Okoma et al., 2025; Rubaihayo, 2002).
Production Resilience	Year-round cultivation despite resource limits; potential for sustainable intensification to address pests, drought, and soil fertility (Okoma et al., 2025; Rubaihayo, 2002).
Socio-Economic Equity	Empowerment of rural women through accessible cultivation; integration with fruits for enhanced household outcomes (Kabunga et al., 2014).

Leafy vegetables occupy a central place in Uganda's agrifood system, both as a dietary staple and as a source of income for rural and peri-urban households. They are among the most affordable and accessible sources of essential micronutrients, including iron, calcium, vitamin A, and vitamin C, which are critical for preventing malnutrition and micronutrient deficiencies (FAO, 2021b; Maseko et al., 2017). The commonly consumed species such as amaranth (*Amaranthus* spp.), Ethiopian kale (*Brassica carinata* A. Braun), spinach (*Spinacia oleracea*

L.), and sweet potato [*Ipomoea batatas (L.)* Lam.] leaves are cultivated across diverse agro-ecological zones and are integral to traditional diets (Food Plant Solutions, 2021).

The nutritional importance of leafy vegetables is underscored by their role in improving dietary diversity, particularly among vulnerable groups such as children and women of reproductive age (Ayenew, et al., 2018). Regular consumption of dark green leafy vegetables has been linked to improved iron status, reduced risk of vitamin A deficiency, and better overall health outcomes (FAO, 2021b). In addition to their health benefits, leafy vegetables are valued for their short growth cycles, which allow for multiple harvests per year, providing a steady food supply and income stream for smallholder farmers (Food Systems Profile - Uganda, 2023).

From an agronomic perspective, leafy vegetables are adaptable to a range of production systems, including home gardens, intercropping arrangements, and increasingly, soilless cultivation methods. Many species are resilient to local pests and diseases, and some indigenous varieties are well adapted to Uganda's climatic conditions, requiring fewer external inputs (Food Plant Solutions, 2021). This adaptability makes them an important component of climate-smart agriculture strategies aimed at enhancing resilience and sustainability in the agrifood system.

Economically, leafy vegetables contribute to household income through sales in local markets, urban street vending, and supply to institutional buyers such as schools and hospitals. The growing demand for fresh, nutrient-rich produce in urban centres presents opportunities for smallholders to integrate into higher-value horticultural value chains (FAO, 2024). However, challenges such as post-harvest losses, limited cold storage, and fluctuating market prices continue to constrain the sector's potential.

Given their nutritional, economic, and agronomic value, leafy vegetables represent a strategic entry point for interventions aimed at improving food security, dietary diversity, and rural livelihoods in Uganda. Integrating innovations such as soilless cultivation and tailored fertilizer regimes could further enhance their productivity and nutritional quality, aligning with national goals for sustainable agrifood system transformation.

1.1.2 Overview of soilless cultivation in Uganda

Soilless cultivation in Uganda is particularly relevant to the production of leafy vegetables, which are vital for both nutrition and income generation among smallholder and urban farmers (Gumisiriza et al., 2022a). Leafy greens such as amaranth, spinach, collard greens, and lettuce are fast-growing, nutrient-dense crops that thrive in controlled environments like hydroponic systems. These systems allow for precise nutrient delivery and water management, which is especially beneficial for leafy vegetables that require consistent moisture and nutrient availability to maintain their quality and yield. Studies conducted in Uganda have shown that hydroponically grown lettuce and amaranth exhibit improved leaf number, shoot height, and root development compared to soil-grown counterparts, making soilless cultivation a promising approach for enhancing leafy vegetable production (Gumisiriza et al., 2022b, 2023).

Moreover, leafy vegetables are highly perishable and sensitive to soil-borne diseases, which make soilless systems even more advantageous. By eliminating soil as a growth medium, farmers can reduce the risk of contamination and improve post-harvest quality. Simplified hydroponic setups like the Kratky method (Kratky, 2009; Ubroda, 2024) have proven effective for growing leafy greens in urban settings, offering a low-cost, low-maintenance solution that supports household nutrition and food security. As Uganda continues to urbanize and face climate-related challenges, integrating soilless cultivation into leafy vegetable farming can help meet the growing demand for fresh, nutritious produce while promoting sustainable agricultural practices (Fuentes-Peñailillo et al., 2024a).

1.1.3 Organic and inorganic fertilizers use in leafy vegetable production

Agriculture began organically. For many centuries, humans farmed without synthetic biocides or inorganic fertilizers, relying on organic fertilizers derived from plants and animals, and protecting crops from pests and diseases using naturally-occurring materials. From the second half of the nineteenth century, growers around the world successfully developed and refined farming systems that relied on synthetic biocides or inorganic fertilizers (Manoharan, 2021). Agriculture was practiced in ancient times without the use of synthetic chemicals. In the middle of the 19th century, the use of synthetic chemicals like insecticides and fertilizers became routine, to the point of overuse. As agriculture became more intensive, with the irrational use of synthetic chemicals agroecosystems was damaged by these unsound agricultural practices. In the 20th century, organic farming developed as a reaction to these unsustainable farming methods. Comparing organic agricultural methods to conventional farming, the yields are lower. Compared to conventional farming systems, organic production methods can yield food products of equal or greater nutritional quality, often with reduced or negligible pesticide residues. These systems are frequently associated with enhanced profitability and demonstrate stronger alignment with environmental stewardship (Mohamed et al., 2018). The substitution of synthetic pesticides with biological or organic inputs, alongside the use of organic amendments for crop fertilization, represents a practice that mitigates ecological risks and promotes sustainability. Consequently, organic food production contributes positively to both human health and environmental well-being.

Organic farming, which excludes the use of synthetic pesticides and fertilizers, has gained increasing global prominence in recent years Mohanapriya et al. (2022).The COVID-19 pandemic further accelerated this trend by heightening consumer awareness of health, nutrition, and food safety. Consequently, the demand for organic fruits and vegetables has expanded worldwide, driven by rising consumption patterns and constrained production capacity.

Abawari, (2022) noted that with the demand changing, use and consumption of natural products have been growing, so there has been greater interest in research in this area. Added to this interest is the concern of environmental impact caused by chemical inputs. Soil fertility management strategies for improving plant nutrients and crop productivity include the use of application of composts, vermicomposts and manures. The use of organic materials is regarded as a workable alternative to increasing the productive potential of soils in situations where there is a limited supply of conventional fertilizers. Due to the scarcity of studies on the utilization of plant leftovers as a source of nutrients, many potentially useful plant residues or materials go unused (Partey et al., 2016). Since organic manures typically enhance the soil's physical, chemical, and biological qualities, using them to satisfy a crop's nutritional needs might become standard practice for sustainable agriculture in the years to come (Adekiya et al., 2020).

Organic and inorganic fertilizers play a pivotal role in enhancing the productivity of leafy vegetables, which are essential for nutritional security in many regions, including sub-Saharan Africa. Empirical evidence indicates that the combined application of organic and inorganic fertilizers can simultaneously enhance crop yield and sustain soil health in leafy vegetable production systems. For example, the integration of organic compost with chemical fertilizers has been shown to promote leaf expansion, improve nutrient uptake, and increase biomass accumulation in lettuce, while also mitigating the risk of heavy metal contamination in soils (Hossain & Ryu, 2018a). Such integrated nutrient management strategies align with the principles of sustainable intensification, particularly in resource-constrained farming contexts where long-term soil productivity is essential. In addition, foliar supplementation with organic nutrients has emerged as a complementary practice that stimulates vegetative growth and minimizes adverse environmental impacts (Bandera & Magolama, 2023).

Economic analyses also suggest that organic fertilizers can be profitable under certain conditions. A study in Nigeria revealed that farmers using commercial organic fertilizers achieved higher yields and a marginal rate of return of 229%, despite facing challenges such as bulkiness and odor (Alimi et al., 2007). However, the cost-effectiveness of organic inputs depends on market prices, availability, and farmer perceptions. In many cases, inorganic fertilizers remain the preferred choice due to their ease of use and immediate results, although their long-term sustainability is questionable. In any case, in many rural areas inorganic fertilizers are either not available or not affordable for smallholder farmers.

Ultimately, the choice between organic and inorganic fertilizers in leafy vegetable production should be guided by agroecological conditions, crop requirements, and socioeconomic factors. While inorganic fertilizers offer short-term gains, organic inputs contribute to soil health and environmental sustainability. A balanced, site-specific fertilizer strategy potentially integrating both types can help farmers achieve optimal yields, improve nutritional quality, and support resilient food systems (Alimi et al., 2007; Bandera & Magolama, 2023; Hossain & Ryu, 2018b; Tabaglio et al., 2015).

Inorganic fertilizers, particularly those rich in potassium (K), are valued for their high solubility and immediate nutrient availability, which can rapidly stimulate crop growth. However, their overuse has been linked to negative consequences, including soil degradation, nutrient imbalances, and increased risks of leaching losses. In tropical agro-ecosystems such as Uganda, potassium leaching is especially pronounced in sandy soils under high rainfall, though nitrogen and phosphorus remain the most critical limiting nutrients for crop productivity. Excessive reliance on K fertilizers without balanced nutrient management may therefore contribute not only to reduced soil fertility but also to broader environmental concerns such as water pollution and ecosystem disruption (Tamale et al., 2021).Conversely, organic amendments such as compost, manure, and plant residues contribute to improved soil structure, enhanced microbial activity, and sustained fertility over time (Hossain & Ryu, 2018a). Although the nutrient release from organic sources is comparatively slower and less predictable, their long-term benefits for soil health are well documented (Griengo et al., 2023)

Although nitrogen (N) is widely recognized as the most limiting nutrient in Ugandan soils due to continuous cropping and high leaching losses under rainfall conditions, potassium (K) also plays a critical role in crop productivity and soil fertility. The emphasis on K in this study stems from its importance in leafy vegetable growth and quality, as well as its susceptibility to depletion in certain soil types with low cation exchange capacity, particularly sandy or highly weathered soils common in parts of Uganda. While N losses through leaching are generally more severe, K leaching can occur under high rainfall regimes and in soils with poor nutrient retention, making it a relevant factor to consider alongside nitrogen. Therefore, the focus on potassium does not imply that N is unimportant, but rather highlights that both nutrients can be limiting depending on soil type and management, and that K deserves specific attention in the context of sustainable fertilizer use and crop nutrition in Uganda (Kyomuhendo et al., 2018).

Table 2:Comparison: Organic versus inorganic fertilizers

Feature	Organic Fertilizers	Inorganic Fertilizers
Nitrogen form	Bound in organic compounds (proteins, amino acids)	Readily available as nitrate or ammonium
Release rate	Slow, via microbial mineralization	Immediate, water-soluble
Soil impact	Improves soil organic matter, microbial activity	Can cause leaching, acidification if overused
Nitrogen content variability	Highly variable (e.g., *Tithonia diversifolia* ~3–4% N)	Standardized concentrations (e.g., NPK 15:15:15 has 15% N)
Sustainability	Renewable, reduces dependence on chemicals	High yield boost but environmental risks

Source: (A. Ahmad et al., 2025; Yeasmin et al., 2025)

A notable limitation of organic fertilizers is the variability in nutrient percentages. Unlike inorganic fertilizers, which provide standardized nutrient concentrations (for example, NPK 15:15:15 guarantees 15% nitrogen, phosphorus, and potassium), organic sources such as compost, manure, or green biomass often show wide fluctuations in nutrient content depending on their origin, season, and decomposition stage. For instance, *Tithonia diversifolia* leaves may contain approximately 3–4% nitrogen, but this value is not fixed and can vary considerably. This inconsistency makes precise nutrient management challenging, as farmers cannot easily predict the exact nutrient supply or synchronize it with crop demand. Consequently, there is a risk of under-application, leading to nutrient deficiencies and reduced yields, or over-application, which may cause nutrient imbalances and inefficiencies. This limitation highlights why organic fertilizers are often complemented with inorganic sources to balance reliability with sustainability (A. Ahmad et al., 2025; Yeasmin et al., 2025).Given this variability in nutrient content, there is a clear need to investigate optimized combinations of growing media and fertilizer types that can ensure consistent nutrient supply, enhance crop performance, and promote sustainable use of agricultural by-products such as coffee husk.

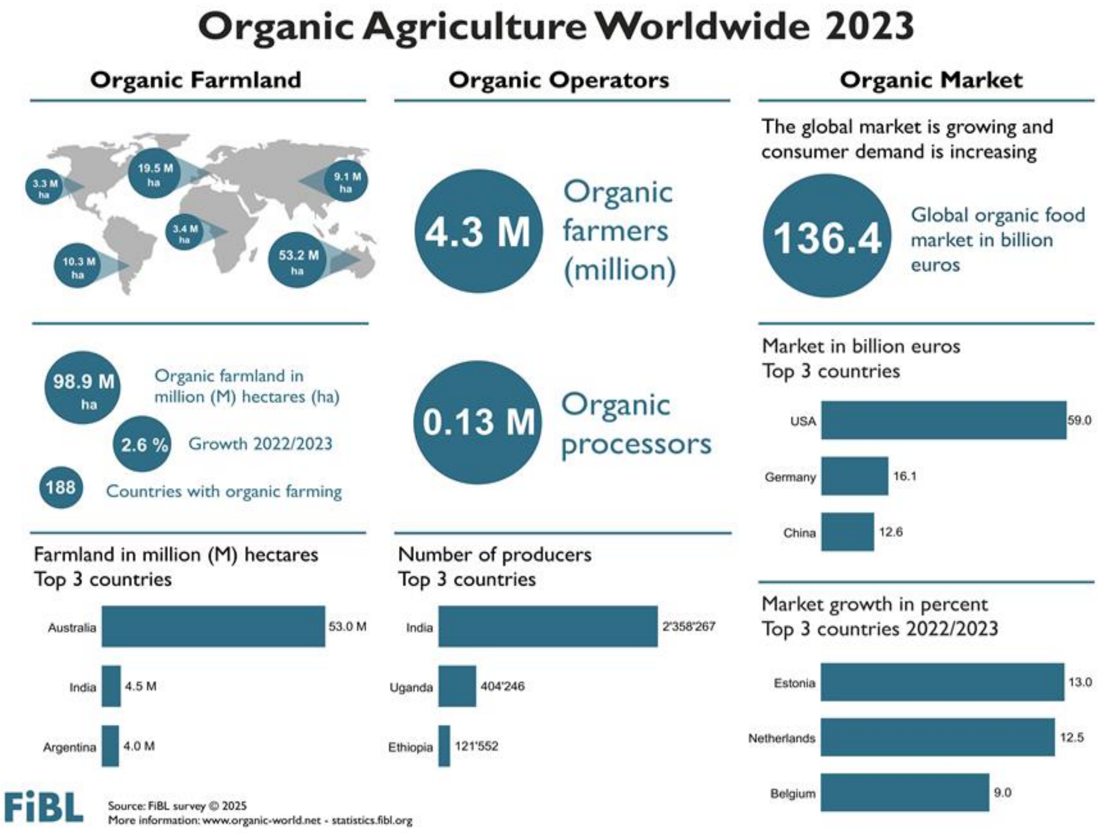


Figure 1:Global distribution of organic Agriculture (FiBL and IFOAM, 2025).

In 2023, global sales of organic food reached nearly €136 billion, with organic fruits and vegetables representing one of the fastest-growing segments (FiBL and IFOAM, 2025). Specifically, the organic fruits and vegetables market is expected to grow from USD 73.2 billion in 2024 to USD 153.7 billion by 2034 (Market.us, 2025).This imbalance between supply and demand underscores the growing importance of organic produce in modern food systems.

Globally, organic agriculture has continued to expand, reaching over 76 million hectares of certified organic farmland in 2023, with consumer demand for organic products rising steadily across Europe, North America, and Asia (Research Institute of Organic Agriculture (Willer et al., 2023) . Uganda stands out as one of the top three producers of organic products worldwide, largely due to its favourable climate, fertile soils, and strong export orientation. This positioning gives Uganda a competitive edge in supplying organic coffee, cotton, and fresh produce to international markets, where demand for chemical-free and sustainably grown products is accelerating (Ronner et al., 2023).

Uganda's prominence in organic production presents significant opportunities for rural development, income diversification, and environmental sustainability. The country's organic sector is projected to increase exports by 40% in the near term, driven by rising global health consciousness and eco-friendly consumption patterns. For smallholder farmers, organic certification not only opens access to premium markets but also reduces reliance on costly synthetic inputs, thereby improving resilience against price unpredictability. Moreover, organic farming aligns with Uganda's national goals of sustainable agriculture and climate adaptation, making it a strategic pathway for long-term food security (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2023).

An emerging opportunity lies in integrating organic fertilizers into soilless cultivation systems, particularly for leafy vegetables such as spinach, kale, and lettuce. Soilless systems like hydroponics or substrate-based cultivation allow for efficient water use, reduced pest pressure, and year-round production. When enriched with organic fertilizers derived from compost, manure, or bio-slurry, these systems can produce nutrient-dense vegetables while maintaining organic certification standards (Fuentes-Peñailillo et al., 2024b)

The adoption of soilless organic systems could transform Uganda's agricultural landscape by diversifying production beyond traditional export crops. Leafy vegetables grown organically in controlled environments would not only meet domestic nutritional needs but also create new export niches in regional and global markets. Additionally, integrating organic fertilizers into soilless systems reduces environmental footprints, supports circular economy practices, and enhances food safety. This synergy between Uganda's organic leadership and innovative cultivation methods positions the country as a model for sustainable agriculture in Africa and beyond (Lakhiar et al., 2025a).

1.1.4 Tithonia (*Tithonia diversifolia* L.)

Tithonia is common in Uganda, Kenya, Tanzania, South Africa, Malawi, and some areas of Zambia. Throughout much of Africa, invasive Tithonia species are common and continuing to expand. It has proven to be an Arenosol-adapted plant with great potential for usage as feed globally. It is regarded as an invasive plant with a high capacity for adaptation that can serve a variety of functions, including serving as a substitute source of food for many animal species. Farmers are using Tithonia more and more as they become aware of its high biomass accumulation, good nutritional value, and ability to thrive in tropical situations (Silva et al., 2020). Mexican sunflower (*Tithonia diversifolia)* also known as is an invasive shrub belonging to the family Asteraceae that grows in tropical regions of South America, Asia, and Africa. It is used as a green biomass to increase soil fertility as well as a traditional medicine, and as a decorative plant (Orsomando et al., 2016).

Tithonia has a strong fertilizing power and the potential to improve over time not only the soil characteristics but also the nutrient levels in the palm organs when grown as a green manure crop in coconut farms (Senarathne et al., 2019a). It has been frequently planted for its decorative and soil fertility-enhancing features, and in new areas it has turned into a renowned environmental weed (Kriticos & Kriticos, 2021). Given the high cost and restricted availability of synthetic fertilizer, using organic fertilizers may be a viable option. Solid or liquid organic fertilizers (LOF) are the two most popular forms of organic fertilizer. Tithonia, a broadleaf plant with high levels of N, P, and K, is frequently used to enrich LOF (Puteri et al., 2021).

Due to its high nitrogen content (≈3.17% in leaves), *Tithonia diversifolia* has been used as a source of green manure (Susanti et al., 2018). It has also been used as green manure in some regions of Africa, Latin America, and Asia. This is due to the plant's quick growth cycle, high capacity for nitrogen fixation, high tissue phosphorus accumulation, and improved ability to access nutrients like phosphorus in depleted soils (Scrase et al., 2019). In some cases, Tithonia can be considered a weed that produces a lot of biomass and has good nutrient content, making it a viable composting material (Pelu et al., 2020). In agriculture, organic matter helps preserve soil fertility. Green leaf biomass of *Tithonia diversifolia* is known to be a potential source of green manure for numerous crops because they are rich in plant nutrients (Senarathne et al., 2019b).

Nitrogen Content in *Tithonia diversifolia* as an Organic Fertilizer

Nitrogen is a vital macronutrient for plant growth, influencing protein synthesis, chlorophyll formation, and overall crop productivity. While inorganic fertilizers supply nitrogen in readily available forms such as nitrate and ammonium, organic sources provide nitrogen bound in complex compounds that become available through microbial mineralization, thereby supporting sustained soil fertility and reducing leaching losses. Among organic inputs, *Tithonia diversifolia* has proven particularly effective due to its high nitrogen content, with leaf concentrations ranging between 3–4%, levels comparable to some inorganic fertilizers (Jama et al., 2000) .Its rapid decomposition ensures nutrient release in synchrony with crop demand, improving uptake efficiency and yields in resource-constrained systems (Geisseler et al., 2021). Recent findings further highlight its role in enhancing nitrogen cycling and reducing losses compared to other organic amendments (Breza & Grandy, 2025).Collectively, the high nitrogen concentration, rapid mineralization, and synchrony with crop needs make *Tithonia diversifolia* a superior organic fertilizer that enhances crop nutritional quality while contributing to sustainable soil fertility management in smallholder systems.

1.1.5 Utilization of charcoal residues and crop by-products as sustainable soilless growing media for leafy vegetable production

Charcoal dust, a fine by-product of wood combustion and charcoal production, is increasingly recognized as a useful component in soilless substrates because its highly porous structure enhances aeration while simultaneously improving water-holding capacity and nutrient retention(FAO, 2021a).These properties support vigorous root development and reduce nutrient leaching, making charcoal dust a sustainable alternative to conventional growing media (Gruda, 2019). When combined with other organic materials, it provides a balanced substrate suitable for leafy vegetables such as amaranth and spinach. For instance, a study conducted in Uganda demonstrated that a mixture of charcoal dust and coffee husks (4:1 ratio) significantly improved the growth rate of *Amaranthus cruentus* L., with notable increases in shoot height, leaf number, and root length compared to conventional soil-based media (Chemutai et al., 2019). This evidence suggests that charcoal dust can serve as a viable substitute for mined soil, particularly in urban and peri-urban agriculture where land resources are limited.

Coffee production has seen an increase in demand over the past 20 years, which has increased the demand for production and is currently driving an expansion in the area under coffee cultivation. However, this rise in output ultimately causes the amount of waste created to increase (San Martin Ruiz et al., 2021). Compost can be used as an ameliorant to enhance soil quality and boost crop production. Coffee husk is one of the organic materials that can be used as compost. The remaining coffee husk has the potential to improve the quality and productivity of the plant, but if it is not used, it will also contaminate the environment (Junedi et al., 2022).

According to the USDA Foreign Agricultural Service (2024) report, global coffee production has expanded from approximately 8.7 million Mg in 2013 to 10.5 million tonnes in 2024. Post-harvest processing, which is required to separate beans from the husk, generates substantial quantities of residual biomass. Given that husks constitute nearly 50% of the harvested coffee mass; their mismanagement poses significant environmental risks. The common practice of piling husks at farm sites not only represents an inefficient disposal method but also contributes to waste accumulation and putrefaction, with adverse implications for soil quality, biodiversity, and human health (Zoca et al., 2014). Identifying sustainable alternatives for husk utilization is therefore critical to mitigating these environmental challenges and advancing circular bioeconomy approaches within coffee production systems.

Vermicomposting is a biological process in which earthworms and microorganisms convert organic waste into a nutrient-rich, humus-like material called vermicompost. In agriculture, vermicomposting is used to improve soil fertility, enhance soil structure, increase microbial activity, and supply plants with readily available nutrients in a sustainable and environmentally friendly way (Manzoor et al., 2024). Vermicomposting (organic manure) can be a valuable tool for valorizing this organic waste, while also producing a fertilizer for reuse in agriculture (Karmakar et al., 2015).

Coffee husks are a major agro-industrial waste in coffee-producing countries like Uganda (Kiggundu & Sittamukyoto, 2019a). Coffee husks are rich in organic matter and micronutrients such as potassium, calcium, and magnesium. Their fibrous texture contributes to improved drainage and aeration when used as a substrate. A physico-chemical analysis of coffee husks revealed their potential for use in biodegradable applications and as a growing medium due to their high fiber content and nutrient profile (Vivas et al., 2025). These properties make coffee husks particularly suitable for leafy vegetable cultivation, where root oxygenation and nutrient availability are critical for optimal growth.

Spent coffee grounds (SCG), another coffee by-product, have also been evaluated as a partial substitute for peat in nursery substrates. A study on *Brassica* seedlings found that incorporating SCG at 2.5–5% into the growing media improved seed emergence, leaf number, and biomass in crops like broccoli and cabbage. However, higher concentrations (≥10%) led to phytotoxic effects and reduced antioxidant activity, indicating the need for careful formulation (Chrysargyris et al., 2021). These findings highlight the potential of SCG as a nutrient-rich additive for leafy vegetable production, provided its use is optimized to avoid negative impacts on plant physiology.

Combining charcoal dust and coffee husks in soilless media not only supports plant growth but also contributes to circular economy practices by repurposing agricultural waste. This approach aligns with sustainable agriculture goals, reducing reliance on mined soil and synthetic inputs. A recent study demonstrated that composting spent coffee grounds with biochar (a form of charcoal) enhanced microbial diversity and nutrient availability, resulting in improved chlorophyll content and growth performance in leafy vegetables like spinach and garden cress (Ozer et al., 2024). Such integrated use of by-products offers a promising pathway for eco-friendly and productive vegetable cultivation.

1.1.6 Nutritional Importance of Leafy Vegetables

The desire to organically strengthen the immune system is driving an increase in interest in eating nutritionally enhanced foods. In this respect, foodstuffs known as "superfoods" that support overall health and boost the immune system include vegetables high in bioactive chemicals (Cobos & Díaz, 2023). Leafy greens constitute a major component of diets worldwide, providing essential phytonutrients and contributing significantly to dietary diversity, though staple cereals and tubers remain the dominant sources of caloric intake (Sarma & Tr, 2024a).The growing awareness of the importance of vital vitamins and minerals has led to a significant emphasis on the necessity for green leafy vegetables. Due to their quick growth and ability to produce many crops in a season, greens are among the most prolific plants in terms of nutritional value per unit area. They provide adequate levels of several minerals as well as vitamins A and C (Shikha Markam, 2022). The green leafy vegetables that are rich in phytochemicals are powerful antioxidants.

According to more recent studies, plant-based diets are rich in vitamins, minerals, and, possibly most importantly, phytonutrients. These phytonutrients are known to have pleiotropic effects on cellular structure and function, which ultimately lead to improved outcomes through the control of protein kinases and subsequent epigenetic alteration (Minich, 2019). In addition to being high in vitamins, minerals, and fiber, leafy greens also contain bioactive substances that support anti-inflammatory and antioxidant properties. They promote general health by lowering the risk of chronic diseases like cardiovascular disease, type-2 diabetes, and several types of cancer, thanks to their high nutrient-to-energy ratios (Sarma & Tr, 2024b). They may have anti-diabetic, anti-cardiovascular diseases, anti-hypertensive, anti-carcinogenic, anti-anemic, and gut-healthy effects (Aslam et al., 2020).

Studies have also shown that regular use of these low-calorie, high-nutrient-to-energy ratio meals improves micronutrient status in people with marginal diets (Jiménez-Aguilar & Grusak, 2017). Furthermore, important nutrients, including vitamins, minerals, and antioxidants, are found in wild and underutilized green plants, which improve diets and economies. Considering species differences and developmental stages, increasing their utilization in food systems enhances sustainability and nutritional quality while fostering food security (Mila et al., 2024). Incorporating a greater variety of leafy greens into regional food systems can help communities become more resilient to environmental and economic shocks while also improving the amount and quality of their diets. These leafy greens reduce household food insecurity scores by mitigating seasonal shortages and diversifying dietary sources due to their affordability, local availability, and adaptability to a range of growing circumstances (Ngidi, 2023; Uusiku et al., 2010a).

1.1.6.1 Spinach (*Spinacia oleracea* L.) is widely regarded as a powerhouse of nutrients, offering substantial health benefits due to its rich composition of vitamins, minerals, and phytochemicals. It is particularly high in iron, calcium, magnesium, and vitamin A, which are essential for blood formation, bone health, and immune function. Spinach also contains significant levels of antioxidants such as β-carotene, lutein, and zeaxanthin, which help reduce oxidative stress and support visual health (Waseem et al., 2021a). Its high protein content and fiber levels contribute to satiety and digestive health, making it a valuable component of diets aimed at combating malnutrition and chronic diseases in low-resource settings (Waseem et al., 2021b).

Spinach is widely recognized as one of the most nutrient-rich green leafy vegetables, offering a robust profile of vitamins, minerals, and phytochemicals. It contains high levels of vitamin A, vitamin C, folate, iron, calcium, and magnesium, which contribute to its role in supporting immune function, bone health, and red blood cell formation (Balasubramaniam et al., 2025; Ramaiyan et al., 2020). According to Martirosyan (2025), spinach is considered a functional food due to its abundance of bioactive compounds like carotenoids, flavonoids, and phenolic acids, which help regulate oxidative stress and metabolic pathways. These compounds also stimulate satiety hormones and reduce food intake, making spinach beneficial in weight management and metabolic health.

Beyond its micronutrient density, spinach exhibits therapeutic properties that make it valuable in preventing chronic diseases. Regular consumption of spinach has been linked to anti-cancer, anti-obesity, hypoglycemic, and hypolipidemic effects due to its ability to modulate gene expression and inhibit inflammatory pathways (Roberts & Moreau, 2016). Spinach-derived phytochemicals scavenge reactive oxygen species and reduce oxidative damage, which is crucial in preventing age-related diseases such as cardiovascular disorders and type 2 diabetes. Its versatility, being consumable raw, cooked, or processed, enhances its accessibility and integration into diverse dietary patterns across cultures and seasons (Kim et al., 2022).

Spinach also plays a strategic role in food security and sustainable agriculture. It is a fast-growing crop that thrives in temperate climates and can be cultivated year-round, including in marginal environments (Singh et al., 2018). A recent study in India highlighted spinach's antibacterial activity and its potential to support nutritional security among smallholder farmers (Singh et al., 2024). Its low cost and high yield make it an ideal candidate for addressing micronutrient deficiencies in vulnerable populations. Moreover, its adaptability to various culinary applications from salads to soups ensures widespread acceptance and utilization, reinforcing its importance as a cornerstone of healthy diets.

1.1.6.2 Cowpea [*Vigna unguiculata* (L.) Walp.] is a dual-purpose crop used for both its seeds and leaves, plays a critical role in food and nutritional security across sub-Saharan Africa. The leaves are rich in protein, dietary fiber, potassium, and essential micronutrients such as folate and iron. Cowpea leaves also contain bioactive compounds, including flavonoids and phenolic acids, which exhibit antioxidant and anti-inflammatory properties (Affrifah et al., 2022). Their affordability and adaptability to various agroecological zones make cowpea a strategic crop for addressing protein-energy malnutrition and enhancing dietary diversity, especially in rural Ugandan communities.

Cowpea, a legume, is a popular source of high-quality plant protein throughout the world. Cowpeas are a significant source of protein and carbohydrates in the human diet, have a low-fat content compared to other plant foods, and have an amino acid profile that complements that of cereal grains. Due to its inherent health-beneficial qualities, including anti-diabetic, anti-cancer, anti-hyperlipidemic, anti-inflammatory, and anti-hypertensive ones, cowpea has recently attracted greater attention from consumers and researchers worldwide. The inclusion of substances, including soluble and insoluble dietary fibre, phytochemicals, proteins, and peptides in cowpea is credited with the presence of the most confirmed mechanisms among those that have been proposed for the protection of chronic diseases (Datta, 2020; Jayathilake et al., 2018).

As a food crop, the cowpea legume is one of the least expensive sources of protein (Moussa Mohamadou et al., 2023). Everywhere in the world, people eat legumes as a basic food. They are the main protein source in some of the world's least developed nations, but their advantages go far beyond their nutritional value. Bioactive substances found in legumes, such as peptides, polyphenols, and saponins, have been shown to have biological effects on inflammation, hypertension, and antioxidants. Therefore, these substances may offer an alternative to current treatments for inflammatory disorders, particularly chronic inflammation found in conditions like cancer, arthritis, and obesity. Alternative medicines made from natural ingredients are becoming more popular today (Juárez-Chairez et al., 2020).

The cowpea is a nutrient-dense food with particularly high protein content. Nutraceutical substances, dietary fibre, antioxidants, polyunsaturated fatty acids, and polyphenols are also abundant in cowpeas (Carneiro Da Silva et al., 2019a). The cowpea is a legume that is widely grown and consumed and is crucial to the nutrition and health of millions of people worldwide. The cowpea has a high relative productivity, stable output, and strong resistance to environmental challenges like drought, in addition to being healthy and secure (Carneiro Da Silva et al., 2021). Additionally, cowpea is economically viable, has little influence on the environment, and aids in resource conservation and production system sustainability. When compared to other sources of protein, cowpeas are inexpensive, readily available, and safe to eat in the majority of areas (Silva et al., 2018).

The interest in including high proportions of fruits and vegetables in diets has developed as people become more aware of the importance of food composition for human health. A rise in the consumption of legumes, a sustainable source of vital nutrients, especially affordable protein, is particularly relevant for achieving the goal of more balanced diets (Gonçalves et al., 2016). One of the biggest issues facing agriculture today is how to keep agro-food systems sustainable, and the launch of new pulse-based products may present an excellent chance to do so. A nutritionally significant crop, cowpeas are unique in that the entire plant, including the aerial portion, is edible (Carvalho, et al., 2022).

1.1.6.3 Amaranth (*Amaranthus viridis* L.) is a highly nutritious leafy vegetable and pseudo-cereal known for its resilience and adaptability to marginal soils. Nutritionally, amaranth leaves are rich in high-quality protein, calcium, iron, magnesium, and dietary fiber. They also contain bioactive compounds such as squalene, tocopherols, and polyphenols, which contribute to cardiovascular health and metabolic regulation (Sattar et al., 2024a). Amaranth's gluten-free nature and high antioxidant capacity make it suitable for functional foods and therapeutic diets. Its role in climate-resilient agriculture and its cultural relevance in Uganda further underscore its importance in sustainable food systems.

With maize, wheat, and rice making up more than 75% of all grain output, the current levels of production of the main basic food crops are insufficient to meet the predicted world food needs (Shiferaw et al., 2011). As a result, there is a critical need to investigate alternative (underutilized or neglected) crops, like amaranth, that have the potential to be instrumental in sustainable agriculture and their application in nutrient-dense food products. With its large leaves and flowers, amaranth (*Amaranthus* spp.) is one of the oldest food crops in existence (Rastogi & Shukla, 2013a; Yamini et al., 2025). It is regarded as a clever crop since it can withstand heat and drought. Amaranth has a high content of high-quality proteins, fibre, minerals, and bioactive substances and is gluten-free (Singh et al., 2024). Popping, flaking, and grinding the grains produce flour, which is effective. *Amaranthus* was identified a few decades ago as a highly promising plant genus that may offer superior protein, unsaturated oil, and several other beneficial components (D'Amico & Schoenlechner, 2017; Klubicová et al., 2016; Toimbayeva et al., 2025).

Due to its yield potential and nutritional benefits, amaranth, an underutilized crop that is also a cheap source of proteins, minerals, vitamin A, and C, appears to be a future crop that can fulfill this demand. It has also recently attracted international interest (Rastogi & Shukla, 2013b; Yadav & Yadav, 2024). Recent interest in amaranth also stems from its high genetic diversity, phenotypic plasticity, and extreme adaptability to challenging growing environments, resistance to heat and drought, lack of significant disease problems, and ranking among the easiest plants to grow in agriculturally marginal lands.

One of the biggest concerns for the security of the world's food supply is the global climatic variance brought on by climate change. Additionally, it is estimated that more than 2 billion people worldwide experience severe malnutrition, also known as “hidden hunger”. In systems adjusting to large-scale climate change, reliance on a small number of crops could result in the loss of genetic diversity and high fragility of crop breeding (Howard et al., 2022a). In order to address the issues of adaptability to environmental change, biodiversity preservation, and improvement of nutrient quality and quantity to ensure food security, it may be helpful to utilize underutilized species and genetic resources, also known as orphan crops, like amaranths (Magalhães et al., 2024). Additionally, the usage of these substitute crops will contribute to enhancing the positive effects on human health (Ivanišová et al., 2021). Orphan crops are crucial to the world's food and nutrition security and may help ensure the sustainability of food systems in the face of climate change. There is a case for promoting them to sustainably address issues such as escalating drought and water scarcity, food and nutrition insecurity, environmental degradation, and employment development under climate change due to reports of their potential under water shortage (Feyisa, 2022; Mabhaudhi et al., 2019).

Trends in the food sector are encouraging the substitution of organically derived colourants with synthetically manufactured ones in response to rising consumer expectations for healthier foods. The majority of natural colourants sold today are anthocyanins, although betalains have benefits over anthocyanins. Given their diverse colour patterns and well-known dietary status around the world, Amaranthus species make appealing betalain sources. Amaranths as natural food colourants have the benefit of complying with U.S. Food and Drug Administration regulations as "vegetable juice" colourants when cultivated as leafy vegetables (Celli & Brooks, 2017; Howard et al., 2022b).

One of the key elements affecting a food's reception by consumers is its colour. Because they offer a more aesthetically pleasing look and serve as a tool for quality control, synthetic dyes are currently the most widely used food colourant in the food business (Silva et al., 2022). However, the global movement to replace them with safer and healthier food colourants derived from natural resources (plants, microbes, and animals) has quickened due to the growing concern about health and the environment linked to toxicity with synthetic food colourants (Pereira et al., 2024). Additionally, many of these biocolorants not only provide food with a variety of colours but also have biological effects, allowing for their application as nutraceuticals in meals and beverages (Thakur & Modi, 2024).

Due to their appealing health benefits, Amaranthus grains have received a lot of attention. The grains contain processing characteristics (such as those linked to starch) that are comparable to those of ordinary cereals. Amaranth grains contain a considerable amount of protein and are gluten-free. Grain protein has been employed in a variety of food applications, including the creation of edible films and emulsions for the slow release of bioactive substances (Adhikary et al., 2020; Zhu, 2023). Using various enzymes, the proteins were digested to create peptides and hydrolysates that displayed a variety of biological properties, including antioxidant and anti-hypertensive effects, among others. For increased nutritional quality, they have been integrated into staple meals like bread and pasta.

Mankind has long been aware of the advantages plants have for supporting health. Recipes for functional foods, medicines, and nutritional supplements are made using preparations from these sources. Amaranth is currently generating more scientific and commercial interest. This is because of its beneficial biological traits, diverse pharmacological activity, and extensive phytochemical composition. Amaranth is a pseudocereal crop with a dual personality that combines the qualities of food and a product that promotes health (Baraniak & Kania-Dobrowolska, 2022; Sattar et al., 2024b).

1.1.6.4 Collard greens (*Brassica oleracea* L.) are part of the cruciferous vegetable family and are known for their dense nutritional profile. They are particularly rich in calcium, vitamin K, and dietary fiber, which support bone health, blood clotting, and digestive function. Collard greens also contain glucosinolates, which are precursors to bioactive compounds with detoxifying and anti-carcinogenic properties (Canazza et al., 2024a). Their high chlorophyll content and retention during cooking make them ideal for nutrient-preserving food preparations. As a culturally accepted vegetable in Uganda, collard greens contribute to both nutritional adequacy and culinary diversity in local diets.

Collard greens are recognized as nutrient-dense vegetables, ranking among the most health-promoting foods globally (Renju et al., 2014), because they contain certain chemicals that may greatly lower the risk of colon cancers, cruciferous vegetables are incredibly healthy (Gitau et al., 2022). Collard greens have a protective effect against diabetes and can be incorporated into a diabetic patient's diet (Kuca et al., 2025). The consumption of orange flesh sweet potato greens (SPG), purslane (PL), and collard greens (CG) may reduce the risks for cardiovascular disease (CVD) linked to diets high in ω-6:ω-3 fatty acids (Johnson et al., 2019). Cruciferous vegetables are extremely healthy, and some of their ingredients may significantly reduce the risk of colon tumors (Lai et al., 2025).

1.1.7 Research Gap

Uganda’s agrifood system is undergoing rapid transformation driven by urbanization, population growth, land fragmentation, and shifting dietary needs. Furthermore, Uganda faces high rates of micronutrient deficiencies, especially among children and women. Indigenous vegetables like amaranth, spinach, collard and cowpea are rich in vitamins and minerals, but their nutritional potential is underutilized. Understanding how soilless systems and fertilizer types affect nutrient density can help improve dietary diversity and combat malnutrition.

While there have been extensive investigations into soilless growing media and nutrient management, significant gaps remain in understanding the complex interactions between substrate composition and fertilizer efficiency, particularly regarding their combined effects on plant morphological traits such as shoot height, leaf number, and leaf length. Moreover, while yield and resource use efficiency in soilless systems have been well documented, the nutrient profiles of crops, especially indigenous leafy vegetables commonly consumed in Uganda, including amaranth, cowpea, collard and spinach under these conditions, is inadequately explored. Critical knowledge is lacking on how different potting media compositions and fertilizer types influence the nutrient profiles, including protein, carbohydrate, crude fiber, and micronutrient content, of these leafy vegetables. Furthermore, the environmental sustainability implications of substrate-fertilizer combinations remain under-researched, especially their long-term impacts on resource conservation, waste reduction, and ecological footprint within Ugandan agricultural contexts.

Further research is therefore needed to assess the nutrient composition of leafy vegetables grown in various soilless media under different fertilizer regimes. Such studies would provide practical guidance for smallholder farmers and urban growers, supporting strategies that enhance both productivity and nutritional value, and ultimately contribute to improved food security, dietary diversity, and poverty reduction.

1.2 Problem Statement

Uganda faces escalating challenges in achieving sustainable and nutritious food production due to land degradation, urbanization, and limited access to synthetic agricultural inputs. While soilless farming systems offer promising alternatives for smallholder and urban growers, there is a critical lack of empirical data on how different substrate compositions and fertilizer regimes, particularly organic versus inorganic, affect the growth and nutrient content of leafy vegetables. Existing research has largely focused on yield and soil fertility, neglecting the complex interactions between substrate-fertilizer combinations and their influence on plant morphology, nutrient density.

This knowledge gap limits the development of integrated, context-specific strategies that could enhance food security, dietary diversity, and environmental sustainability within Uganda's agrifood system. Without localized evidence on the nutritional outcomes and ecological impacts of soilless vegetable production, farmers and policymakers lack the tools to make informed decisions that align with national goals for climate resilience and public health. Addressing this problem is essential for transforming Uganda's agrifood system into one that is productive, nutritious, and environmentally sound.

1.3 Objectives of the study

1.3.1 Main Objective

To determine the nutritive profiles of selected leafy vegetables grown in soilless growing media enriched with organic fertilizer (Tithonia leaf powder) and inorganic fertilizer.

1.3.2 Specific Objectives

The study was guided by the following specific objectives:

i. To investigate the effects of soilless growth media enriched with organic and inorganic fertilizers on the nutritive profiles of selected leafy vegetables.
ii. To compare the nutritive profiles of selected leafy vegetables grown in enriched soilless media with those grown under soil-based conventional agronomic practices
iii. To determine the effect of different proportions of soilless growth media on the growth and yield performance and nutrient content of selected leafy vegetables.

1.4 Hypotheses of the study

Effect of soilless growth media enriched with fertilizers on the nutritive profile

H_{01} (Null): Soilless growth media enriched with fertilizers have no statistically significant effect on the nutritional profile of leafy vegetables.

H_{11} (Alternative): Soilless growth media enriched with fertilizers have a statistically significant effect on the nutritional profile of leafy vegetables.

Comparison between soilless and conventional soil-based systems

H_{02} (Null): There are no statistically significant differences in the nutritional profile of leafy vegetables grown in soilless growth media compared to those grown under conventional soil-based systems.

H_{12} (Alternative): There are statistically significant differences in the nutritional profile of leafy vegetables grown in soilless growth media compared to those grown under conventional soil-based systems.

Effect of different proportions of soilless media on growth of leafy vegetables

H_{03} (Null): Different proportions of soilless media have no statistically significant effect on growth and yield performance of leafy vegetables.

H_{13} (Alternative): Different proportions of soilless media have a statistically significant effect on growth and yield performance of leafy vegetables.

1.5 Significance of the Study

The findings of this study provided practical approaches for cultivating leafy vegetables using soilless growing media in combination with organic fertilizers, with the aim of enhancing their nutritional quality. The research identified an organic fertilizer option, Tithonia leaf powder that offered potential to reduce vegetable production costs while minimizing reliance on synthetic inputs and mitigating environmental pollution.

In addition, the study demonstrated possible ways of utilizing coffee husks, an agricultural by-product that has historically posed environmental management challenges in areas with high coffee production. By incorporating coffee husks into soilless media, the research contributed to waste valorization and promoted environmentally sustainable farming practices. The outcomes are expected to benefit smallholder farmers, urban growers, policymakers, and other stakeholders seeking to improve vegetable production systems, strengthen food and nutrition security, and advance sustainable agriculture in Uganda and similar contexts.

1.6 Justification of the Study

Soilless cultivation offers a viable solution to the challenge of diminishing arable land, as it enables plants to access essential nutrients directly from a formulated nutrient solution without the need for extensive root systems. This method optimizes space use, enhances nutrient uptake efficiency, and supports crop production in areas where soil quality or availability is limited.

Globally, fertilizer prices have risen at a rate exceeding that of food prices, a trend exacerbated by the effects of the COVID-19 pandemic and other global disruptions, including increased natural gas prices. These factors have disrupted fertilizer production and exports, reduced supply, and driven up costs, thereby threatening agricultural productivity and food availability. According to the FAO report (FAO, 2021b), high fertilizer prices risk transforming the current food affordability crisis into a food availability crisis, with millions of people unable to access healthy diets, leading to food insecurity and various forms of malnutrition. This situation underscores the need for systemic approaches that link short-term recovery to long-term transformation, including diversification of domestic food production.

Micronutrient deficiencies, often referred to as "hidden hunger", are a major contributor to increased susceptibility to infectious diseases, higher morbidity and mortality rates, and long-term disabilities such as cognitive impairment (IFPRI, 2016). Leafy vegetables, being nutrient-dense and rich in essential vitamins and minerals, can play a pivotal role in strategies aimed at reducing poverty, hunger, and malnutrition.

However, contemporary agricultural practices, which in some cases involve the excessive and indiscriminate use of chemical fertilizers and pesticides, can pose significant risks to both human health and the environment. Such practices can lead to the accumulation of harmful residues in the food chain (Ganguly & Banerjee, 2025). This study is therefore justified in exploring sustainable alternatives, specifically the use of soilless growing media enriched with organic fertilizers to improve the nutritional quality of leafy vegetables, reduce production costs, and mitigate environmental pollution.

1.7 Contextual Relevance

In Uganda, where agriculture is dominated by smallholder farmers cultivating on increasingly fragmented plots, the challenges of declining soil fertility, limited access to affordable fertilizers, and vulnerability to climate variability are acute. Rising global fertilizer prices further constrain input use, exacerbating low productivity and poor dietary diversity in rural households. Introducing soilless cultivation systems enriched with locally available organic resources, such as Tithonia leaf powder and coffee husks, offers a practical, low-cost, and environmentally sustainable alternative. Such innovations have the potential to improve the nutritional quality of leafy vegetables, reduce dependence on costly synthetic inputs, and create value from agricultural by-products, directly addressing the intertwined issues of food insecurity, malnutrition, and rural poverty in Uganda's smallholder farming context.

1.8 Scope of the Study

This study was conducted in a greenhouse to evaluate the growth performance and nutritive profiles of four leafy vegetable species: spinach (*Spinacia oleracea* L.), cowpea [*Vigna unguiculata* (L.) Walp.], amaranth (*Amaranthus viridis* L.), and collard greens (*Brassica* *oleracea* L.). The vegetables were cultivated in soilless growing media composed of varying proportions of charcoal dust and coffee husks. Three fertilizer treatments were applied: i) organic fertilizer (Tithonia leaf powder), ii) inorganic fertilizer, and iii) a control with no fertilizer application.

The research focused on assessing the effects of both the type of fertilizer and the proportion of soilless media on plant growth parameters and nutritional composition, including mineral and vitamin content. The scope was limited to the production stage under controlled greenhouse conditions at the Department of Horticulture, Bukalasa Agricultural College, Wobulenzi, Luweero, Uganda (Lat. 0.71322, Long. 32.51444) and findings are therefore most applicable to similar agro-ecological and controlled-environment contexts. Post-harvest handling, storage, processing, and market chain analysis were outside the scope of this study.

1.9 Limitations of the Study

- **Controlled environment**: Conducted in a greenhouse, which may not fully replicate open-field conditions; results may vary under natural environmental stresses.
- **Geographical specificity**: Limited to a single research site, restricting generalizability to other regions with different climates or soils.
- **Crop selection**: Focused on four leafy vegetable species; findings may not apply to other crops.
- **Time frame**: Based on one growing cycle, which may not capture seasonal variations.
- **Nutrient analysis scope**: Concentrated on selected nutritional parameters; other quality attributes, such as phytochemical profiles or sensory properties, were not assessed.

1.10 Conceptual Framework

The conceptual framework was built on the premise that the type of soilless medium (proportion of charcoal dust to coffee husk) and the type of fertilizer (organic, inorganic, or none) are the main independent variables influencing the growth performance and nutritional quality of leafy vegetables. These factors affect nutrient availability and uptake, which in turn determine plant biomass and the concentration of essential vitamins and minerals in edible leaves.

Independent Variables:

- Proportion of charcoal dust: coffee husk in soilless media
- Fertilizer type (organic, inorganic, control)

Dependent Variables:

- Growth parameters (plant height, leaf number, biomass)
- Nutritional composition (Proximate composition crude protein, crude fat, crude fibre, total carbohydrates, total ash)

Controlled Factors:

- Greenhouse environmental conditions (temperature, humidity, light)
- Irrigation/watering schedule
- Pest and disease management

Expected Relationship: Optimized combinations of soilless growing media proportions and fertilizer type are expected to enhance both growth and nutritional quality of leafy vegetables, while promoting sustainable use of agricultural by-products such as charcoal dust and coffee husk.

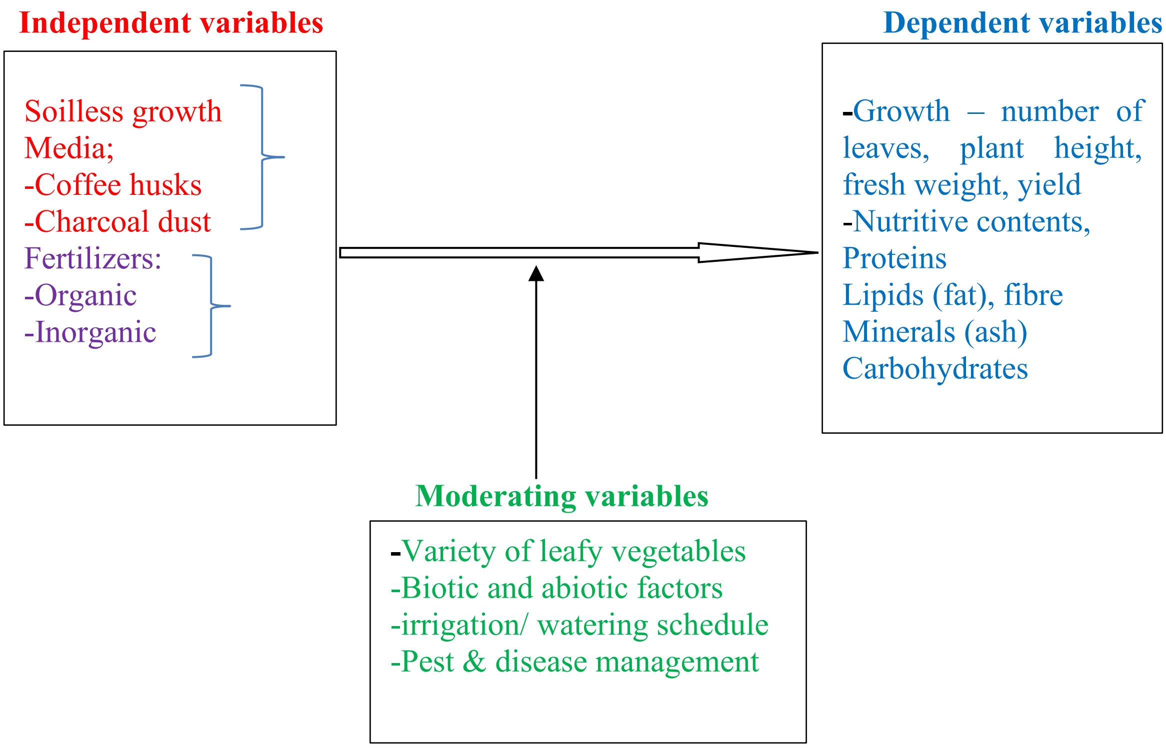


Figure 2:Conceptual framework to guide the research study

***Source**: Designed by the researcher*

1.11 Definition of Terms

For the purpose of this study, the following terms are defined as they are used in the research:

- **Soilless Growing Media** – A plant growth substrate that does not contain natural soil, composed in this study of varying proportions of charcoal dust and coffee husk, used to support plant roots and supply nutrients through applied fertilizers.
- **Charcoal Dust** – Fine particulate residue from charcoal production, used here as a component of soilless media to improve aeration and drainage.
- **Coffee Husk** – The dry outer covering of coffee beans removed during processing, utilized in this study as an organic component of soilless media and as a means of recycling agricultural waste.
- **Organic Fertilizer** – A plant nutrient source derived from natural materials; in this study, Tithonia [*Tithonia diversifolia* (Hemsl.) A. Gray] leaf powder was used for its high nutrient content and potential to improve soil-less media fertility.
- **Inorganic Fertilizer** – A commercially manufactured, mineral-based fertilizer applied in this study as a comparative nutrient source to organic fertilizer.
- **Control (No Fertilizer)** – Experimental treatment in which no fertilizer was applied, serving as a baseline for comparing the effects of organic and inorganic fertilizers.
- **Leafy Vegetables** – Edible plants whose leaves are consumed as food; in this study, spinach (*Spinacia oleracea* L.), cowpea [*Vigna unguiculata* (L.) Walp.], amaranth (*Amaranthus viridis* L.), and collard greens (*Brassica oleracea* L.) were evaluated.
- **Nutritional Profile** – The composition of essential nutrients in the edible leaves of the vegetables, including minerals, vitamins, and other relevant nutritional parameters measured in this study.
- **Growth Performance** – The measurable physical development of plants, including parameters such as plant height, number of leaves, and biomass yield.
- **Greenhouse** – A controlled environment structure used in this study to regulate temperature, humidity, and light for optimal plant growth and to minimize external environmental variability.
- **Tithoni*a* [**Tithonia diversifolia (Hemsl.) A. Gray]- In this thesis, the names *Tithonia*, *Mexican sunflower*, and *Tithonia diversifolia L.* are used interchangeably to refer to the same plant species. This species was applied as an organic fertilizer treatment in the experiments.
- **Nutrient Content / Nutrient Quality / Nutrient Composition / Nutritive Profiles** These terms are used synonymously throughout the thesis to denote the measured nutrient content of the leafy vegetables studied. Parameters include crude protein, carbohydrate, fibre, ash, fat, dry matter, and iron.
-

1.12. List of Abbreviations

Abbreviation	Full term description
%	Percentage (used for nutrient composition)
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists (standard methods for food and agriculture analysis)
CEC	Cation Exchange Capacity: The total capacity of a soil or substrate to hold exchangeable cations.
DM	Dry Matter
EC	Electrical Conductivity
FAO	Food and Agriculture Organization of the United Nations
FR1	Fertilizer Treatment 1 (Organic)
FR2	Fertilizer Treatment 2 (NPK – Nitrogen, Phosphorus, Potassium)
FR3	Fertilizer Treatment 3 (No fertilizer)
GM1	Treatment 1 (2:1 charcoal dust: coffee husks)
GM2	Treatment 2 (1:1 charcoal dust: coffee husks)
GM3	Treatment 3 (1:2 charcoal dust: coffee husks)
Ha	Hectare
H_0	Null Hypothesis
H_1	Alternative Hypothesis
HSD	Honestly Significant Difference (Tukey's test)
kg ha^{-1}	kilograms per hectare (fertilizer or yield application rate)
mg $100g^{-1}$	milligrams per 100 grams
µg	micrograms
Mg ha^{-1}	Megagrams per hectare (equivalent to tonnes per hectare, yield measurement)
NPK	Nitrogen, Phosphorus, Potassium (common inorganic fertilizer formulation)
t ha^{-1}	Tonnes per hectare (yield or application rate)

CHAPTER 2. MATERIALS AND METHODS

This chapter outlines the methodological framework employed to investigate the effects of fertilizer regimes and soilless media compositions on the morphological traits and nutrient profiles of selected leafy vegetables. Given the growing interest in sustainable agriculture and the need for nutrient-rich vegetables in Uganda, a controlled experimental approach was adopted to generate reliable, reproducible data under standardized conditions. The study was conducted in a greenhouse to minimize environmental variability and isolate the effects of media and fertilizer treatments.

A split-plot design was selected to efficiently examine the interaction between potting media ratios and fertilizer types across the selected vegetable species. This design allowed for robust statistical analysis while maintaining experimental control. Four leafy vegetables: spinach (*Spinacia oleracea* L.), cowpea [*Vigna unguiculata* L.) Walp.], amaranth (*Amaranthus viridis* L.), and collard (*Brassica oleracea* L. var. *acephala*), were chosen based on their nutritional importance and adaptability to greenhouse cultivation. Each crop was grown in three soilless media formulations composed of charcoal dust and coffee husk, and subjected to three fertilizer regimes: organic Tithonia [*Tithonia diversifolia* (Hemsl.) A. Gray)], inorganic (NPK 15:15:15), and a control with no fertilizer.

In addition to the greenhouse experiment, a comparative study was conducted using peer-reviewed literature to benchmark the nutrient composition of soil-grown counterparts. This dual approach, experimental and comparative, provided a comprehensive understanding of how cultivation systems influence the nutritional quality of leafy vegetables.

The following sections detail the experimental design, materials used, planting procedures, growing conditions, fertilizer application rates, nutrient analysis techniques, quality control measures, statistical tools employed to analyze the data and comparative nutritional benchmarking.

2.1 Experimental site and design description

This study was conducted in a controlled greenhouse environment at the Department of Horticulture, Bukalasa Agricultural College, Wobulenzi, Luweero, Uganda (Lat. 0.71322, Long. 32.51444), to evaluate the effects of different fertilizer types and soilless potting media on the nutrient composition of selected leafy vegetables. The greenhouse provided a regulated setting that minimized external influences such as soil variability, pests, and extreme weather conditions, thereby ensuring that observed treatment effects could be attributed primarily to the experimental factors. The experimental design employed a split-plot layout with four replications, a methodological choice driven by both the hierarchical nature of the treatments and the need for efficient resource allocation. In this study, the potting media ratios (charcoal dust: coffee husks) represented the main plot factor, while fertilizer regimes constituted the subplot factor. A split-plot design was more appropriate than a randomized complete block design because the main plot treatments required larger, more uniform experimental units to minimize variability in substrate preparation and application. By contrast, fertilizer treatments could be applied more flexibly and uniformly within smaller subplots nested inside each main plot. This hierarchical structuring allowed for precise estimation of both main effects and interaction effects, while reducing logistical complexity and experimental error. Furthermore, the split-plot design enhanced statistical reliability by accommodating the differential precision with which the two factors could be applied and measured. In an RCBD, all treatment combinations would need to be randomized across blocks at the same scale, which would have imposed impractical demands on substrate preparation and increased the risk of confounding variability. The split-plot approach therefore provided a balance between experimental control and operational feasibility, ensuring that the larger-scale potting media treatments were applied consistently, while still allowing rigorous testing of fertilizer regimes within each block.

This design also improved efficiency in terms of resource use, as it reduced the number of large-scale substrate preparations required, while still maintaining replication and randomization at both the main plot and subplot levels. By structuring the experiment in this way, the study was able to generate statistically valid comparisons of both factors and their interactions, without compromising the integrity of the greenhouse environment or overextending available resources. In sum, the split-plot design was deliberately selected over a randomized complete block design because it aligned with the practical realities of substrate preparation and fertilizer application, while simultaneously strengthening the statistical validity of the analysis. This methodological choice ensured that the research outcomes were both reproducible and robust, reflecting a careful balance between theoretical rigor and experimental feasibility.

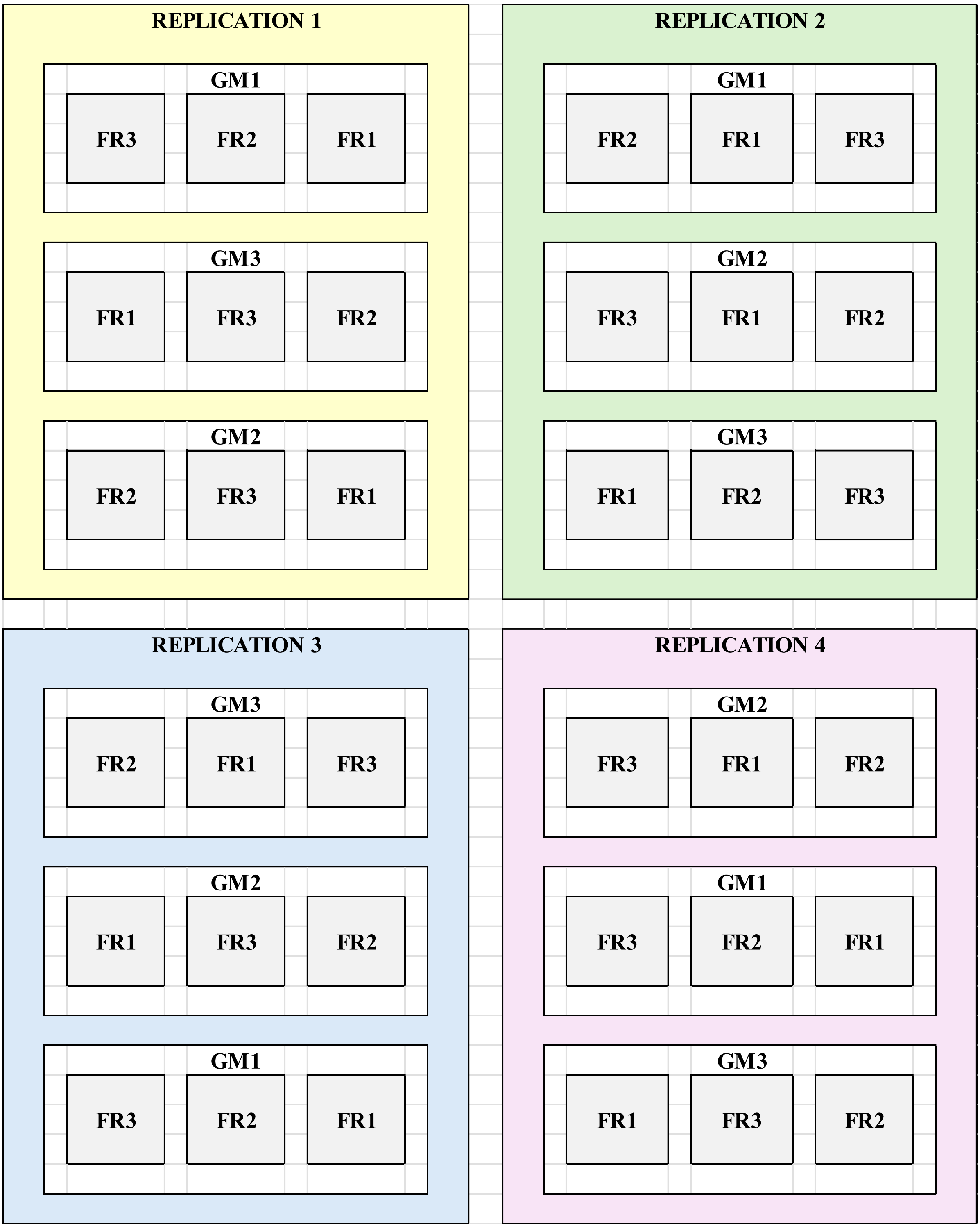


Figure: 3 Layout of the Experiment (Replications, Main Plots GMx, Subplots FRx)

2.1.2 Soilless potting media

A combination of charcoal dust (CD) and coffee husks (CH) was used in varying proportions to formulate the soilless media. Three different ratios were prepared: CD: CH = 2:1, 1:1, and 1:2. These materials were selected due to their high organic matter content, excellent aeration properties, and potential to enhance nutrient retention, making them suitable alternatives to conventional soil-based media. Charcoal dust provides structural support and helps retain essential nutrients, while coffee husk contributes organic matter that supports microbial activity and promotes plant health. In line with the study's objective of assessing functional performance, charcoal dust and coffee husk were utilized in their natural state, and particle size distribution was not characterized.

2.1.3 Fertilizer regimes

Two types of fertilizer were applied to assess their effects on the nutrient composition of the selected leafy vegetables.

i. Organic fertilizer
   The organic fertilizer was derived from fresh tithonia [*Tithonia diversifolia* (Hemsl.) A.Gray)] leaves, a fast-growing plant known for its high nitrogen content. Young, tender leaves were harvested, chopped, and sun-dried before being incorporated into the potting media as an organic fertilizer. Tithonia is valued as an organic soil amendment for its ability to release nutrients gradually, thereby improving long-term soil fertility. Leaf nitrogen concentrations typically range between 3–4%, which is relatively high compared to many other organic inputs, although values may vary depending on growing conditions and plant maturity.

ii. Inorganic Fertilizer
   A commercial NPK (15:15:15) fertilizer was applied at recommended rates for leafy vegetables. This synthetic fertilizer provides a balanced supply of Nitrogen, Phosphorus, and Potassium nutrients essential for plant growth, leaf development, and overall crop productivity.

A control treatment (FR3) was also included, in which no fertilizer was applied. This allowed for a clear comparison of the effects of the two fertilizer types on the growth and nutrient composition of the leafy vegetables.

2.2 Selected vegetables

Four different leafy vegetable species were selected based on their nutritional value, local diet and preferences in Uganda, commercial importance, and adaptability to greenhouse cultivation: cowpeas [*Vigna unguiculata* (L.) Walp, green amaranth (*Amaranthus viridis* L.), collard (*Brassica oleracea* L.) and spinach (*Spinacia oleracea* L.).

2.3 Seed Sourcing and Planting

Certified seeds were bought from a reputable agricultural input supplier and supplemented with seeds sourced from the Department of Horticulture at Bukalasa Agricultural College. The seeds of cowpeas and amaranth were sown directly into the prepared potted media under controlled conditions, while collard and spinach were first raised in nursery trays within the greenhouse and later transplanted into pots with soilless growth media.

2.4 Growing Conditions

All leafy vegetables were grown in a greenhouse, ensuring consistent temperature and humidity levels conducive to plant growth. The controlled environment minimized external factors such as excessive rainfall or soil-borne diseases, allowing for a more accurate assessment of treatment effects. Temperatures ranged between 25 °C and 28 °C throughout the experiment, while relative humidity remained between 60% and 80%, providing optimal moisture conditions for plant development, while at the same time avoiding the proliferation of fungal diseases. The vegetables were watered twice daily (morning and evening) using a watering can to maintain adequate moisture levels in the growing media.

2.5 Fertilizer Application

2.5.1 Organic Fertilizer Application

Organic fertilizer was applied at a rate of 3 Mg ha^{-1} (300 g m^{-2}). It was thoroughly mixed with the potting media before planting to allow for decomposition and gradual nutrient release.

2.5.2 Inorganic Fertilizer Application

Inorganic fertilizer (NPK 15:15:15) was applied at a rate of 200 kg ha^{-1} (20 g m^{-2}), thus providing 30 kg ha^{-1} of each nutrient. For amaranths and cowpeas, it was incorporated into the potting media before planting. For collards and spinach, the fertilizer was applied at transplanting to minimize nutrient leaching and optimize uptake.

2.6 Nutrient Content Analysis and Yield determination

Each selected vegetable was hand-harvested, weighed to determine its fresh weight, and promptly transported to the laboratory for analysis. Nutritional composition was assessed using proximate analysis, following standardized methods established by the (Association of Official Analytical Chemists, 2000), to ensure precision and comparability with existing literature. The parameters evaluated included moisture content, crude protein (via total nitrogen determination), and crude fat (by ether extraction). Total ash content was determined through furnace incineration, while total carbohydrates were calculated by difference. Crude fiber was quantified using sequential acid and alkaline digestion. Yield was assessed using dry matter weight, obtained after oven-drying samples to constant weight. Dry matter was selected as the basis for yield determination to avoid variability caused by moisture content.

2.7 Quality Control Measures

To ensure data reliability and uphold research rigor, multiple quality control measures were implemented. Each treatment was replicated four times to minimize experimental variability. Planting density was standardized per species: three plants per pot for cowpeas, five for amaranths, and one each for spinach and collard. All experimental protocols adhered to Association of Official Analytical Chemists (AOAC) International standards and agronomic best practices. These quality assurance protocols strengthened the reliability and reproducibility of the findings, enhancing their relevance for future agricultural applications.

2.8 Statistical Analysis

To evaluate the effects of fertilizer type, potting media, and their interaction, both descriptive and inferential statistical methods were applied. A two-way analysis of variance (ANOVA) was performed to determine the significance of the main factors and their interaction. Where significant differences were detected, Tukey's Honest Significant Difference (HSD) post-hoc test was employed to identify significant differences among treatment means. All statistical analyses were performed using R software.

2.9 **Comparative Nutritional Benchmarking**

In addition to the greenhouse experiment, a comparative study was conducted to evaluate the nutritional profiles of leafy vegetables grown in soilless media versus those cultivated under conventional soil-based agronomy. The objective was to benchmark the nutrient composition of spinach (*Spinacia oleracea* L.), cowpea [*Vigna unguiculata* L. Walp.], amaranth (*Amaranthus viridis* L.), and collard (*Brassica oleracea* L.) across different cultivation systems. Peer-reviewed literature was systematically reviewed using academic databases such as Google Scholar, ResearchGate, SpringerLink, and MDPI. Search terms included "soil-grown leafy vegetables," "nutrient composition," "organic vs. inorganic fertilizer," and "soilless vs. soil-based systems." Studies were selected based on clear documentation of fertilizer treatments, standardized nutrient reporting (per 100g dry weight), and robust statistical analysis. Nutrient parameters extracted included crude protein, carbohydrate, fiber, fat, ash, dry matter, and iron. Data were standardized and organized into comparative tables, categorizing each vegetable by treatment type (organic or inorganic) and cultivation system (soilless or soil-based). This approach enabled a reliable comparison of nutritional outcomes and helped contextualize the experimental findings within broader agronomic practices.

CHAPTER 3: RESULTS AND DISCUSSION

This chapter presents and interprets the findings derived from the greenhouse experiment and comparative analysis outlined in Chapter 2. The results focus on the morphological traits and nutrient profiles of four leafy vegetables: spinach, cowpea, amaranth, and collard, grown under varying fertilizer regimes and soilless medium compositions. The data are organized to highlight the influence of organic and inorganic fertilizers, as well as the effect of media ratios composed of charcoal dust and coffee husks. Morphological traits such as shoot height, leaf count, and leaf length are examined to assess vegetative vigor and growth performance. Nutritional parameters, including crude protein, carbohydrate, fiber, fat, ash, dry matter, and iron content, are analyzed to evaluate the dietary value of the crops. In addition to experimental results, this chapter integrates findings from a comparative study of soil-grown leafy vegetables sourced from peer-reviewed literature. This benchmarking provides context for evaluating the performance of soilless systems relative to conventional soil-based cultivation. The discussion interprets these results in light of existing research, agronomic principles, and the broader goal of promoting sustainable vegetable production in Uganda. Emphasis is placed on identifying optimal combinations of fertilizer and medium that enhances both yield and nutritional quality, with implications for food security, resource efficiency, and climate-resilient agriculture.

3.0 Results

3.1 Effects of organic and inorganic fertilizers on yield and nutrient composition of leafy vegetables grown in soilless potting mixes

Consistent with the methodological approach, yield was determined using dry matter measurements. The results section therefore presents treatment comparisons based on dry matter yield.

3.1.1 Yield of leafy vegetables

In this thesis, yield was expressed on a dry weight basis to minimize variability caused by water content and to provide a more accurate measure of nutrient accumulation. While fresh weight is commonly reported in market-oriented studies, dry yield was selected here to better reflect the agronomic impact of the treatments

The effects of fertilizer enrichment across three soilless growth media (GM1: 2:1, GM2: 1:1, GM3: 1:2 charcoal dust to coffee husks) were evaluated on the yield and dry matter content of four leafy vegetables. Fertilizer treatments included FR1 (organic fertilizer derived from *Tithonia diversifolia*), FR2 (inorganic NPK), and FR3 (control with no fertilizer). Results revealed crop-specific responses to both media composition and fertilizer type (Table 4)

Table 3: Crop-specific responses to growth media composition and fertilizer type

Crop	Media (CD:CH)	Fertilizer Type	Dry Matter (%)	Yield (t·ha^{-1})
Spinach	GM3 (1:2)	FR2 (NPK)	94.5	7.524
Spinach	GM3 (1:2)	FR1 (Organic)	93.2	7.381
Spinach	GM3 (1:2)	FR3 (Control)	92.8	7.358
Cowpea	GM2 (1:1)	FR1 (Organic)	87.06	6.932
Cowpea	GM2 (1:1)	FR2 (NPK)	78.5	6.773
Cowpea	GM2 (1:1)	FR3 (Control)	85.3	6.847
Amaranth	GM3 (1:2)	FR1 (Organic)	90.46	7.202
Amaranth	GM3 (1:2)	FR2 (NPK)	89.8	7.141
Amaranth	GM3 (1:2)	FR3 (Control)	89.0	7.171
Collard	GM2 (1:1)	FR2 (NPK)	91.46	7.282
Collard	GM2 (1:1)	FR1 (Organic)	89.3	7.207
Collard	GM2 (1:1)	FR3 (Control)	84.93	7.205

Note*: Yield values are reported as dry matter yield (t·ha^{-1}), calculated from oven-dried samples to constant weight. This approach excludes variability due to moisture content and reflects the actual biomass productivity of the crops.*

Spinach recorded the highest yield (7.524 t·ha^{-1}) in GM3 enriched with FR2, followed closely by FR1 (7.381 t·ha^{-1}) and the control (7.358 t·ha^{-1}). Cowpea greens achieved peak yield (6.932 t·ha^{-1}) in GM2 with FR1, outperforming both FR2 and the control. Amaranth exhibited minimal yield variation, with the highest value (7.202 t·ha^{-1}) in GM3 with FR1. Collard attained its maximum yield (7.282 t·ha^{-1}) in GM2 with FR2. The dry matter content ranged from 78.5% (cowpea greens under FR2) to 94.5% (spinach under FR2), indicating treatment-specific physiological responses. Percentage yield increases relative to the control were modest but consistent in spinach and collard under FR2, and in cowpea greens and amaranth under FR1 (Table 5). Notably, cowpea greens under FR2 showed a slight yield reduction (–1.08%), suggesting potential suppression of biological nitrogen fixation.

Table: 4 Percentage yield increases relative to the control

Crop	Media (CD:CH)	Fertilizer type	% Yield increase versus control
Spinach	GM3 (1:2)	FR2 (NPK)	+2.26%
Spinach	GM3 (1:2)	FR1 (Organic)	+0.31%
Cowpea Greens	GM2 (1:1)	FR1 (Organic)	+1.24%
Cowpea Greens	GM2 (1:1)	FR2 (NPK)	–1.08%
Amaranth	GM3 (1:2)	FR1 (Organic)	+0.43%
Amaranth	GM3 (1:2)	FR2 (NPK)	–0.42%
Collard	GM2 (1:1)	FR2 (NPK)	+1.07%
Collard	GM2 (1:1)	FR1 (Organic)	+0.03%

Spinach

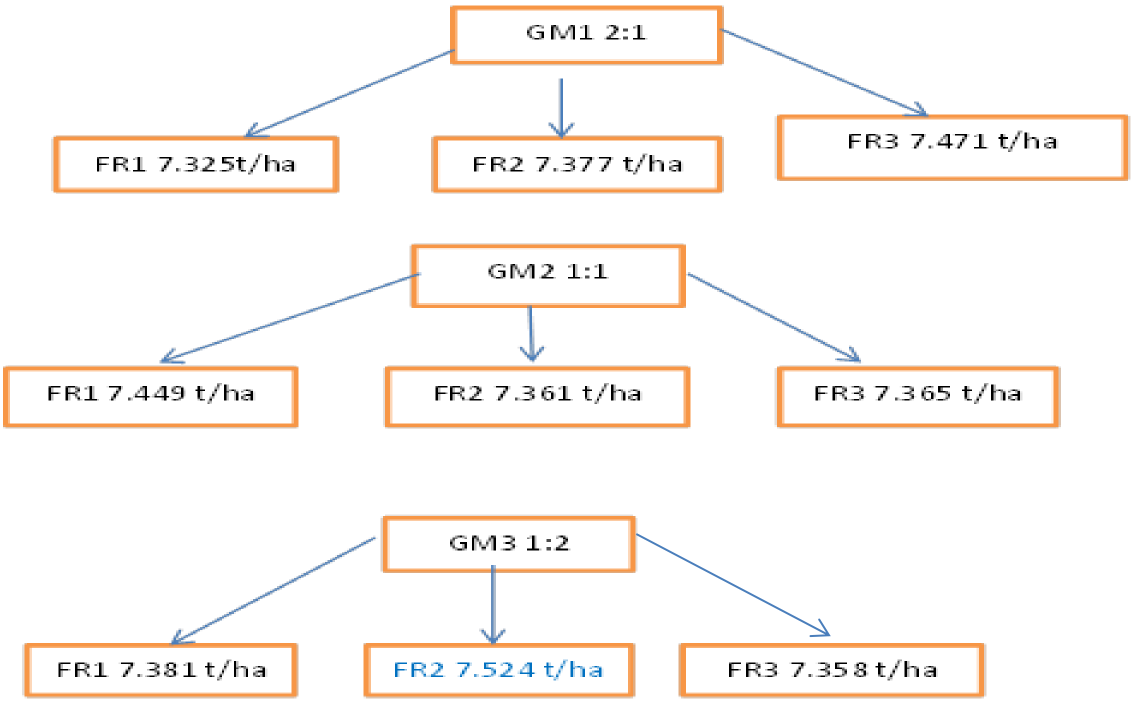


Figure 4: Spinach yield performance across three soilless media proportions and fertilizers.

The highest spinach yield (7.524 t·ha⁻¹) was recorded in the 1:2 charcoal dust: coffee husks media proportion with NPK fertilizer. This exceeded both the control (7.358 t·ha⁻¹) and organic fertilizer (7.381 t·ha⁻¹) treatments. Other media ratios (2:1 and 1:1) yielded slightly lower averages (~7.39 t·ha⁻¹). Dry matter content remained consistently high (92–94.5%) across treatments.

Cowpea Greens

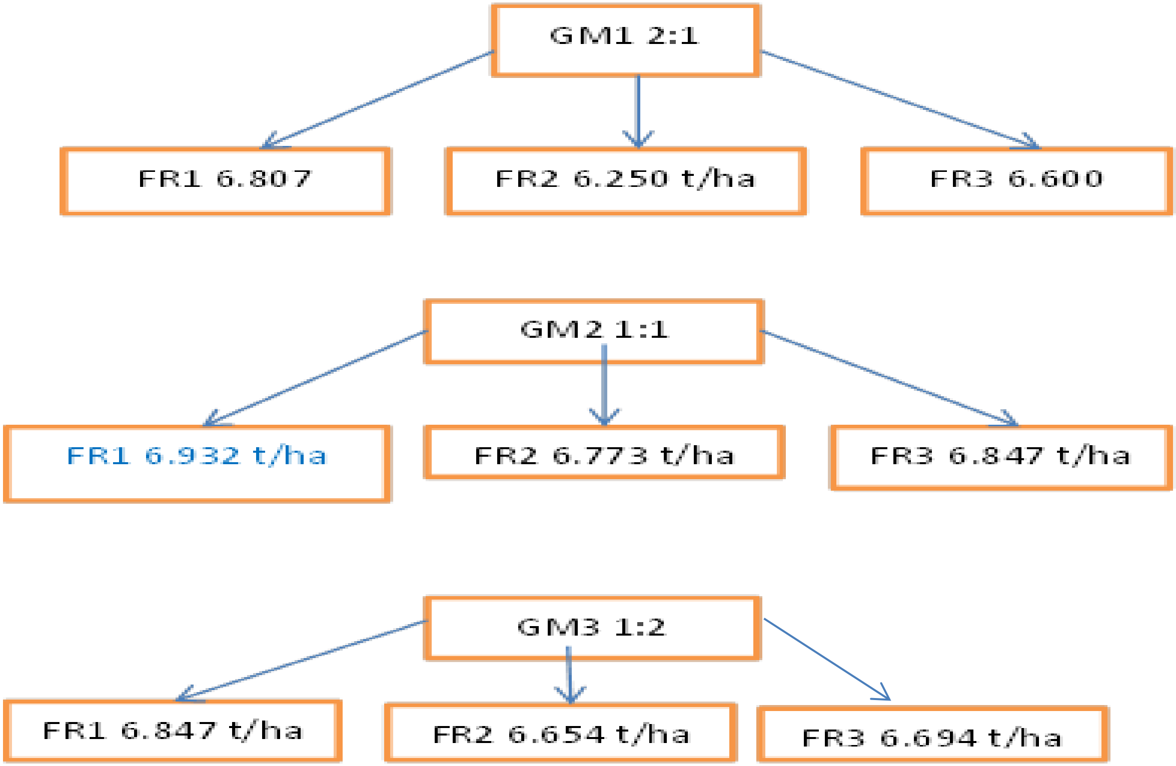


Figure 5: Cowpea yield variations across media proportions and different fertilizers

Maximum yield (6.932 $t{\cdot}ha^{-1}$) was achieved in the 1:1 media with organic fertilizer, outperforming both NPK (6.773 $t{\cdot}ha^{-1}$) and control (6.847 $t{\cdot}ha^{-1}$) in the same substrate. The lowest yield (6.250 $t{\cdot}ha^{-1}$) occurred in the 2:1 media with NPK. Dry matter content ranged from 78.5% to 87.06%.

Amaranth

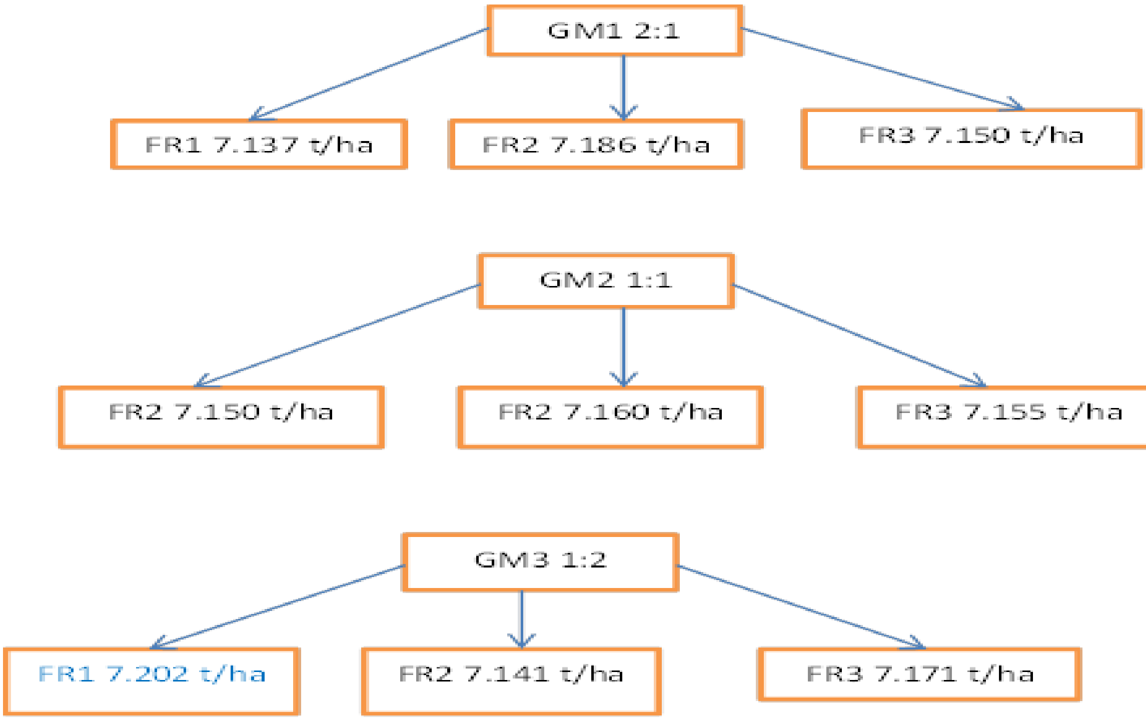


Figure 6: Amaranth yield stability across media proportions and fertilizers

Yield variation was minimal (0.9%), with the highest yield (7.202 t·ha^{-1}) in the GM3 (1:2) media with organic fertilizer. Control (7.171 t·ha^{-1}) and NPK (7.141 t·ha^{-1}) treatments yielded comparably. Dry matter content remained stable (89–90.46%).

Collard

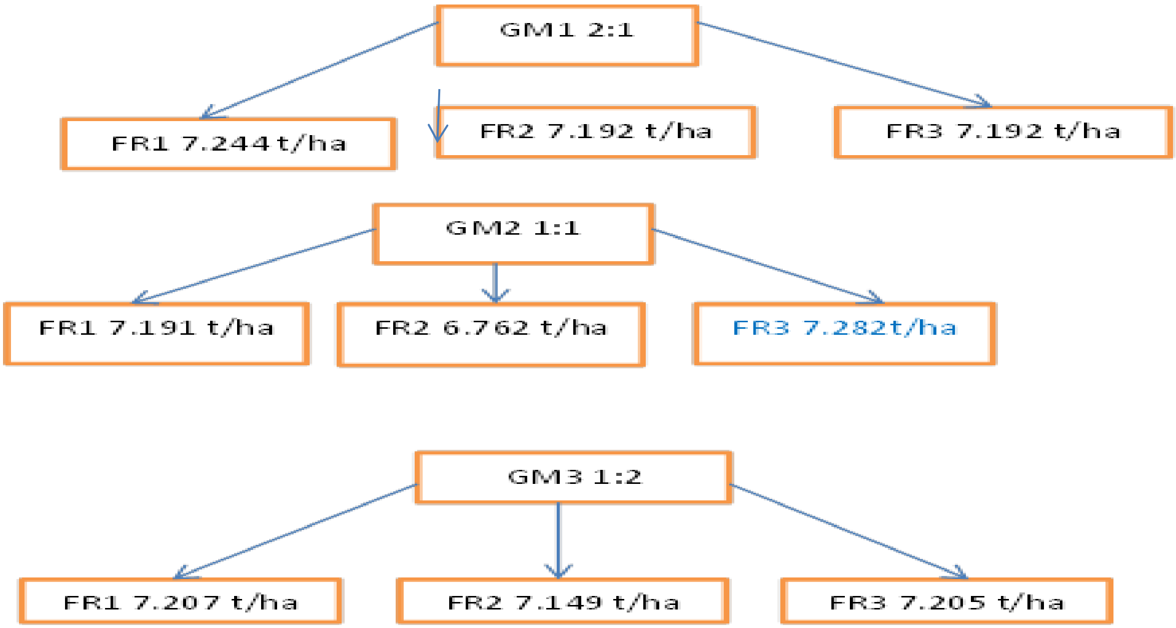


Figure 7: Collard yield distribution across media proportions and fertilizers

The highest yield (7.282 t·ha^{-1}) was observed in the 1:1 media with NPK, slightly exceeding the control (7.205 t·ha^{-1}) and organic fertilizer (7.207 t·ha^{-1}). However, an anomalously low yield (6.762 t·ha^{-1}) was also recorded under NPK in the same media. Dry matter content ranged from 84.93% to 91.46%.

Yield response to growth media and fertilizer treatments

ANOVA Summary

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Growth media	2	18.7	9.35	0.62	0.546
Fertilizer type	2	12.4	6.20	0.41	0.667
Growth media × Fertilizer	4	21.6	5.40	0.36	0.834
Residuals	24	356.9	14.87	—	—

Two-way ANOVA revealed that growth media, fertilizer type, and their interaction did not significantly affect yield ($p > 0.05$). However, vegetable type accounted for substantial variation, with spinach consistently producing higher yields (7.524 t·ha^{-1}) compared to collard, cowpea, and amaranth. These findings suggest that inherent crop characteristics exert a stronger influence on yield than the tested media and fertilizer regimes, although observed trends indicate that GM3 combined with NPK fertilizer tended to support slightly higher yields in spinach and amaranth.

3.1.2 Nutrient composition of leafy vegetables

While nutrient composition is often expressed on a fresh weight basis to reflect dietary relevance, in this thesis values were reported on a dry matter basis to ensure accurate comparison across treatments, given the variability in moisture content.

Table 5: Mean nutrient Composition of spinach leaves under different treatments

Source of variation	Dry Matter (%)	Total Ash (%)	Crude Fibre (%)	Crude Fat (%)	Crude Protein (%)	Total Carbohydrate (%)	Iron (mg/100g)
Main factor: Soilless medium							
GM1 (2:1)	92.83^{c}	24.72^{ab}	6.81^{b}	7.39^{b}	23.91^{b}	30.67^{a}	0.03^{ab}
GM2 (1:1)	92.84^{c}	24.62^{ab}	6.99^{ab}	6.83^{b}	23.98^{b}	30.42^{a}	0.02^{bc}
GM3 (1:2)	93.21^{a}	24.42^{b}	7.46^{a}	9.97^{a}	26.06^{a}	25.30^{c}	0.02^{bc}
Secondary Factor: Fertilizer Type							
FR1 (Organic)	92.76^{c}	25.08^{a}	7.51^{a}	7.17^{b}	22.47^{c}	29.86^{a}	0.02^{bc}
FR2 (NPK)	93.20^{a}	24.71^{ab}	6.49^{c}	9.15^{a}	27.03^{a}	25.83^{c}	0.03^{ab}
FR3 (None)	92.92^{bc}	23.97^{b}	7.26^{ab}	7.21^{b}	23.79^{b}	30.69^{a}	0.02^{bc}
Interaction: Soilless Medium × Fertilizer Type							
GM1 + FR1 (2:1 + Organic)	92.00^{c}	24.50^{ab}	7.46^{a}	6.50^{d}	19.44^{d}	34.09^{a}	0.04^{a}
GM1 + FR2 (2:1 + NPK)	92.65^{bc}	25.00^{a}	6.00^{c}	9.00^{b}	27.95^{a}	24.70^{c}	0.03^{ab}
GM1 + FR3 (2:1 + None)	93.84^{a}	24.66^{ab}	6.96^{ab}	6.67^{d}	22.35^{c}	33.21^{ab}	0.02^{bc}
GM2 + FR11 (1:1 + Organic)	93.56^{a}	25.74^{a}	7.37^{a}	5.50^{e}	22.10^{c}	32.86^{ab}	0.02^{bc}
GM2 + FR2 (1:1 + NPK)	92.46^{bc}	25.63^{a}	6.47^{bc}	7.50^{c}	25.52^{ab}	27.35^{bc}	0.01^{c}
GM2 + FR3(1:1 + None)	92.50^{bc}	22.50^{c}	7.14^{ab}	7.50^{c}	24.31^{b}	31.05^{bc}	0.02^{bc}
GM3 + FR1 (1:2 + Organic)	92.71^{bc}	25.00^{a}	7.69^{a}	11.50^{a}	25.87^{ab}	22.64^{c}	0.01^{c}
GM3 + FR2 (1:2 + NPK)	94.50^{a}	23.50^{bc}	7.00^{ab}	10.95^{a}	27.62^{a}	25.43^{c}	0.04^{a}
GM3 + FR3 (1:2 + None)	92.42^{c}	24.75^{ab}	7.69^{a}	7.46^{c}	24.70^{b}	27.82^{bc}	0.02^{bc}
Trial Mean	**92.96**	**24.59**	**7.09**	**7.73**	**24.65**	**30.46**	**0.02**

Superscript letters within each column indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing the same letter are not significantly different

The nutrient composition of spinach leaves was significantly influenced by the soilless medium and fertilizer type, as well as their interaction (Table 6). Among the main factor treatments, spinach grown in GM3 (1:2 charcoal dust: coffee husk) exhibited the highest crude fat (9.97%) and crude protein (26.06%), indicating superior nutrient accumulation under this medium. GM1 and GM2 showed comparable dry matter and ash content, though GM1 supported higher carbohydrate levels. Regarding fertilizer treatments, FR2 (NPK) resulted in the highest crude fat (9.15%) and protein (27.03%), while FR1 (organic) enhanced fibre (7.51%) and iron (0.02 mg/100g) content. The interaction effects revealed that the combination of GM1 + FR1 produced the highest carbohydrate (34.09%) and iron (0.04 mg/100g), whereas GM1 + FR2 yielded the highest protein (27.95%). Notably, GM2 + FR1 recorded the lowest fat content (5.50%), suggesting that organic fertilizer may suppress lipid synthesis under a 1:1 medium.

Overall, the trial mean values across all treatments were 92.96% dry matter, 24.65% crude protein, 7.73% crude fat, 30.46% total carbohydrate, and 0.02 mg/100g iron, confirming spinach as a nutritionally dense leafy vegetable under optimized growing conditions. These findings indicate that spinach consistently accumulates high levels of dry biomass and protein, making it a valuable source of dietary amino acids. The moderate fat content, coupled with substantial carbohydrate levels, suggests a balanced energy contribution. Iron concentration remained relatively stable across treatments, reinforcing spinach's reputation as a reliable source of micronutrients. These results support the recommendation of spinach for both nutritional and agronomic value under varied soilless media and fertilizer regimes.

Table 6: Mean nutrient composition of cowpea leaves under different soilless media and fertilizer treatments

Source of variation	Dry Matter (%)	Total Ash (%)	Crude Fibre (%)	Crude Fat (%)	Crude Protein (%)	Total Carbo-hydrate (%)	Iron (mg/100g)
Main factor: Soilless medium							
GM1 (2:1)	82.96[c]	20.34[c]	10.20[b]	3.12[ab]	19.70[c]	28.77[b]	0.03[ab]
GM2 (1:1)	86.21[a]	21.26[b]	10.56[ab]	2.34[b]	22.86[ab]	29.68[ab]	0.02[b]
GM3 (1:2)	84.55[b]	23.25[a]	11.35[a]	2.88[ab]	19.93[bc]	26.47[c]	0.02[b]
Secondary factor: Fertilizer type							
FR1 (Organic)	86.19[a]	21.63[b]	11.18[a]	2.74[b]	19.96[c]	31.00[a]	0.02[b]
FR2 (NPK)	82.38[c]	20.92[c]	10.23[b]	2.95[ab]	25.19[a]	23.26[c]	0.02[b]
FR3 (None)	85.15[b]	22.30[ab]	10.89[ab]	2.72[b]	20.92[b]	30.66[a]	0.03[ab]
Interaction: Soilless Medium × Fertilizer Type							
GM1 + FR1 (2:1 + Organic)	85.50[b]	24.00[a]	10.75[ab]	3.23[a]	18.23[c]	29.28[b]	0.02[b]
GM1 + FR2 (2:1 + NPK)	78.50[c]	14.00[c]	9.40[c]	2.86[ab]	24.31[a]	27.44[c]	0.03[ab]
GM1 + FR3 (2:1 + None)	82.89[b]	23.03[a]	10.45[b]	3.27[a]	16.57[d]	29.58[b]	0.05[a]
GM2 + FR1 (1:1 + Organic)	87.06[a]	18.41[bc]	10.84[ab]	2.50[b]	20.66[bc]	34.66[a]	0.02[b]
GM2 + FR2 (1:1 + NPK)	85.07[b]	22.39[ab]	9.41[c]	3.00[ab]	28.48[a]	21.80[c]	0.01[c]
GM2 + FR3 (1:1 + None)	86.00[a]	23.00[a]	11.44[a]	1.53[c]	19.44[c]	30.58[ab]	0.03[ab]
GM3 + FR1 (1:2 + Organic)	86.00[a]	22.50[ab]	11.94[a]	2.50[b]	19.99[c]	29.07[b]	0.02[b]
GM3 + FR2 (1:2 + NPK)	83.58[b]	26.37[a]	10.89[ab]	3.00[ab]	22.79[bc]	20.54[c]	0.02[b]
GM3 + FR3 (1:2 + None)	84.08[b]	22.89[a]	11.22[a]	3.15[a]	17.01[d]	29.81[b]	0.02[b]
Trial Mean	**84.83**	**21.93**	**10.67**	**2.78**	**21.14**	**28.56**	**0.02**

Superscript letters within each column indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing the same letter are not significantly different

Table 7 showed cowpea leaf nutrient composition was influenced by both soilless media and fertilizer type. GM2 (1:1) resulted in the highest dry matter (86.21%) and protein (22.86%), while GM3 (1:2) led in fibre (11.35%) and ash (23.25%) but had the lowest carbohydrate (26.47%). GM1 (2:1) showed lower protein and dry matter but higher carbohydrate (28.77%). Among fertilizer treatments, FR2 (NPK) produced the highest protein (25.19%) and fat (2.95%), though carbohydrate was lowest (23.26%). FR1 (organic) supported the highest fibre (11.18%) and carbohydrate (31.00%), while FR3 (no fertilizer) maintained balanced nutrient levels with slightly elevated iron (0.03 mg/100g). Interaction effects revealed that GM2 + FR2 yielded the highest protein (28.48%) and fat (3.00%), but the lowest iron. GM1 + FR1 had the highest carbohydrate and iron, while GM3 + FR1 showed the highest fibre and carbohydrate. The overall trial mean values for cowpea were 84.83% dry matter, 21.14% crude protein, 2.78% crude fat, 28.56% total carbohydrate, and 0.02 mg/100g iron.

These figures indicate that cowpea is a leaner leafy vegetable, with lower fat and protein compared to spinach and collard. However, its high fibre and carbohydrate content make it a valuable source of dietary roughage and energy. The consistent iron levels across treatments suggest cowpea can contribute to micronutrient intake, especially when consumed regularly. Overall, cowpea's trial means highlight its role as a complementary vegetable in diversified diets, particularly where low-fat, high-fibre options are preferred.

Table 7: Mean nutrient composition of amaranth leaves under different soilless media and fertilizer treatments

Source of variation	Dry Matter (%)	Total Ash (%)	Crude Fibre (%)	Crude Fat (%)	Crude Protein (%)	Total Carbohydrate (%)	Iron (mg/100g)
Main factor: Soilless medium							
GM1 (2:1)	89.90^{b}	8.76^{c}	4.48^{b}	8.85^{b}	23.12^{b}	43.75^{a}	0.02^{b}
GM2 (1:1)	89.87^{b}	16.41^{a}	4.17^{b}	8.57^{b}	25.55^{a}	35.18^{c}	0.01^{c}
GM (1:2)	90.07^{a}	14.16^{b}	4.22^{b}	8.72^{b}	24.32^{ab}	40.65^{b}	0.02^{b}
Secondary factor: Fertilizer type							
FR1 (Organic)	89.97^{b}	12.59^{b}	4.40^{b}	9.03^{a}	23.75^{b}	42.53^{a}	0.02^{b}
FR2 (NPK)	89.73^{b}	11.71^{b}	4.74^{a}	8.29^{b}	25.03^{a}	36.36^{c}	0.03^{a}
FR3 (None)	90.13^{a}	15.30^{a}	4.73^{a}	8.82^{b}	24.24^{ab}	41.69^{b}	0.01^{c}
Interaction: Soilless Medium × Fertilizer Type							
GM1 + FR1 (2:1 + Organic)	89.64^{b}	3.32^{c}	3.86^{c}	9.65^{a}	23.97^{b}	48.85^{a}	0.03^{a}
GM1 + FR2 (2:1 + NPK)	90.26^{a}	9.00^{bc}	4.83^{ab}	8.46^{b}	22.35^{c}	42.78^{ab}	0.03^{a}
GM1 + FR3 (2:1 + None)	89.81^{b}	13.97^{ab}	4.75^{ab}	8.43^{b}	23.04^{bc}	39.63^{bc}	0.01^{c}
GM2 + FR1 (1:1 + Organic)	89.80^{b}	16.60^{a}	4.18^{bc}	8.23^{b}	22.48^{c}	38.30^{c}	0.02^{b}
GM2 + FR2 (1:1 + NPK)	89.93^{b}	16.55^{a}	3.78^{c}	8.19^{b}	27.70^{a}	33.81^{c}	0.01^{c}
GM2 + FR3 (1:1 + None)	89.87^{b}	16.09^{a}	4.56^{ab}	9.30^{a}	26.48^{ab}	33.44^{c}	0.01^{c}
GM3 + FR1 (1:2 + Organic)	90.46^{a}	17.84^{a}	3.17^{c}	9.20^{a}	23.80^{b}	40.44^{b}	0.03^{a}
GM3 + FR2 (1:2 + NPK)	89.69^{b}	10.57^{bc}	4.65^{ab}	7.47^{c}	25.13^{ab}	41.87^{b}	0.01^{c}
GM3 + FR3 (1:2 + None)	90.07^{a}	14.07^{ab}	4.84^{a}	8.48^{b}	23.03^{bc}	39.65^{bc}	0.02^{b}
Trial Mean	**89.94**	**13.58**	**4.38**	**8.63**	**24.27**	**40.02**	**0.02**

Superscript letters within each column indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing the same letter are not significantly different.

Amaranth leaves exhibited distinct nutrient profiles across treatments, as shown in Table 8. GM3 (1:2) produced the highest dry matter (90.07%) and fibre (4.22%), with strong protein and fat levels. GM2 (1:1) had the highest ash (16.41%) and protein (25.55%) but the lowest carbohydrate (35.18%), while GM1 (2:1) supported the highest carbohydrate (43.75%) and iron (0.02 mg/100g). Fertilizer effects showed that FR2 (NPK) enhanced protein (25.03%) and fibre (4.74%) but reduced carbohydrate. FR1 (organic) promoted higher fat (9.03%) and carbohydrate (42.53%), while FR3 (no fertilizer) had the highest ash and fibre with moderate nutrient levels. Interaction effects revealed that GM1 + FR1 yielded the highest carbohydrate (48.85%) and iron (0.03 mg/100g), while GM2 + FR2 had the highest protein (27.70%) but lower carbohydrate and fibre. GM3 + FR1 showed the highest dry matter and fibre, with strong protein and carbohydrate levels. The trial mean values for amaranth were 89.94% dry matter, 24.27% crude protein, 8.63% crude fat, 40.02% total carbohydrate, and 0.02 mg/100g iron.

These results underscore amaranth as a high-energy leafy vegetable, with the highest carbohydrate content among the four crops studied. Its protein and fat levels were comparable to spinach, suggesting strong nutritional value. The elevated dry matter reflects efficient biomass accumulation, while the consistent iron concentration supports its role in addressing micronutrient deficiencies. Overall, the trial means position amaranth as a versatile and nutrient-rich crop, ideal for enhancing both caloric and protein intake in plant-based diets.

Table 8: Mean nutrient composition of collard leaves under different soilless media and fertilizer treatments

Source od variation	Dry Matter (%)	Total Ash (%)	Crude Fibre (%)	Crude Fat (%)	Crude Protein (%)	Total Carbohydrate (%)	Iron (mg/100g)
Main factor: Soilless medium							
GM1 (2:1)	90.55[ab]	14.99[b]	4.65[b]	7.90[b]	27.19[b]	36.62[ab]	0.01[b]
GM2 (1:1)	88.90[b]	15.44[ab]	4.83[b]	9.10[a]	27.39[b]	32.15[c]	0.01[b]
GM3 (1:2)	90.27[a]	11.70[c]	5.28[a]	8.42[ab]	28.02[a]	36.85[a]	0.01[b]
Secondary factor: Fertilizer type							
FR1 (Organic)	90.61[a]	12.86[c]	5.15[ab]	8.22[ab]	27.64[b]	37.61[a]	0.01[b]
FR2 (NPK)	90.30[ab]	10.45[c]	5.16[ab]	8.94[a]	27.82[ab]	37.52[a]	0.01[b]
FR3 (None)	89.81[b]	17.50[a]	4.80[b]	8.32[ab]	27.31[b]	33.58[bc]	0.01[b]
Interaction: Soilless Medium × Fertilizer Type							
GM1 + FR1 (2:1 + Organic)	90.98[a]	14.20[b]	4.72[b]	7.34[c]	26.76[b]	37.96[a]	0.01[b]
GM1 + FR2 (2:1 + NPK)	90.33[ab]	12.76[c]	4.74[b]	8.66[ab]	28.23[a]	35.95[ab]	0.01[b]
GM1 + FR3 (2:1 + None)	90.35[ab]	16.00[ab]	4.50[b]	7.70[b]	26.57[b]	35.95[ab]	0.01[b]
GM2 + FR1 (1:1 + Organic)	90.32[ab]	13.28[c]	4.77[b]	9.35[a]	27.31[b]	35.62[ab]	0.00[c]
GM2 + FR2 (1:1 + NPK)	84.93[c]	15.06[ab]	4.38[c]	8.47[ab]	27.20[b]	29.83[c]	0.01[b]
GM2 + FR3 (1:1 + None)	91.46[a]	17.99[a]	5.33[a]	9.47[a]	27.66[b]	31.01[c]	0.01[b]
GM3 + FR1 (1:2 + Organic)	90.52[ab]	9.11[c]	5.36[a]	7.97[b]	28.85[a]	39.24[a]	0.01[b]
GM3 + FR2 (1:2 + NPK)	89.79[b]	9.49[c]	5.38[a]	9.10[a]	26.42[b]	39.39[a]	0.01[b]
GM3 + FR3 (1:2 + None)	90.50[ab]	16.51[a]	5.10[ab]	8.20[ab]	28.80[a]	31.91[c]	0.02[a]
Trial Mean	**89.99**	**13.98**	**4.94**	**8.43**	**27.53**	**34.99**	**0.01**

Superscript letters within each column indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing the same letter are not significantly different.

The nutrient composition of collard leaves varied significantly across soilless media and fertilizer treatments as shown in Table 9. Among the main factor treatments, GM3 (1:2 charcoal dust: coffee husk) produced the highest crude fibre (5.28%) and protein (28.02%), along with elevated dry matter and carbohydrate levels, indicating superior nutrient accumulation. GM2 (1:1) yielded the highest crude fat (9.10%) but had the lowest dry matter and carbohydrate content, suggesting a trade-off between lipid and energy compounds. GM1 (2:1) maintained balanced nutrient levels, particularly in carbohydrate (36.62%) and ash (14.99%). Regarding fertilizer effects, FR2 (NPK) enhanced crude fat (8.94%) and protein (27.82%), while FR1 (organic) supported higher fibre (5.15%) and carbohydrate (37.61%). FR3 (no fertilizer) resulted in the highest ash (17.50%) but lower protein and carbohydrate. Interaction effects revealed that GM3 combined with either FR1 or FR2 produced the highest fibre and carbohydrate levels, while GM2 + FR3 recorded the highest ash and fat, but reduced carbohydrate. Overall, the trial mean values for collard were 89.99% dry matter, 27.53% crude protein, 8.43% crude fat, 34.99% total carbohydrate, and 0.01 mg/100g iron.

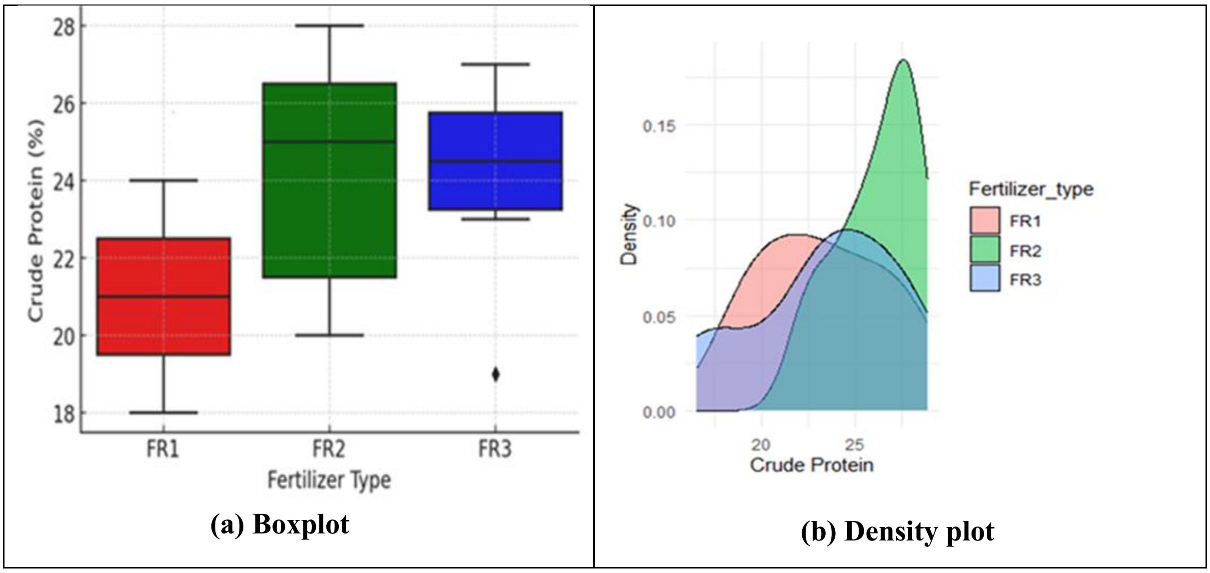
These averages reflect collard's strong potential as a protein-rich leafy vegetable, surpassing spinach in crude protein content. The elevated fat and carbohydrate levels suggest that collard contributes significantly to dietary energy, while maintaining a robust structural profile through its fibre content. Although iron levels were slightly lower than in spinach, the overall nutrient balance positions collard as a highly nutritious crop, particularly suitable for regions aiming to boost protein intake through plant-based sources.

3.1.1 Crude Protein

Table 9: ANOVA summary of crude protein

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Potting media	2	17.06	8.53	1.759	0.19369
Fertilizer type	2	64.19	32.10	6.619	0.00514 **
Potting media: fertilizer type	4	13.96	3.49	0.720	0.58685
Residuals	24	116.38	4.85		

Fertilizer type had a statistically significant effect on crude protein content in the tested leafy vegetables ($p < 0.01$). Post hoc comparisons revealed that both FR1 (organic fertilizer) and FR2 (NPK) treatments resulted in significantly higher crude protein levels compared to the control group (FR3), indicating that both organic and inorganic fertilizers positively influenced protein accumulation. However, no significant difference was observed between FR1 and FR2 themselves. In contrast, neither the main effect of growth media composition ($p = 0.194$) nor the interaction between fertilizer type and media ($p = 0.587$) showed a statistically significant influence on crude protein content.



(a) Boxplot **(b) Density plot**

Figure 8: Crude protein across different fertilizer types

Figure 8 (a) a boxplot and (b) a density plot illustrates the influence of different fertilizer treatments on the crude protein content of leafy vegetables. The NPK fertilizer treatment (FR2) resulted in the highest protein concentrations, as indicated by a higher median value and a broader interquartile range (IQR), reflecting greater variability among replicates. In comparison, the organic fertilizer treatment (FR1) produced moderate protein levels exceeding those observed in the unfertilized control (FR3) but remaining lower than the NPK-treated group. The control group (FR3) exhibited the lowest and most inconsistent protein levels, as evidenced in the boxplot by a compressed IQR and reduced median, and further supported by the density plot, which displayed a more restricted distribution relative to the fertilized treatments.

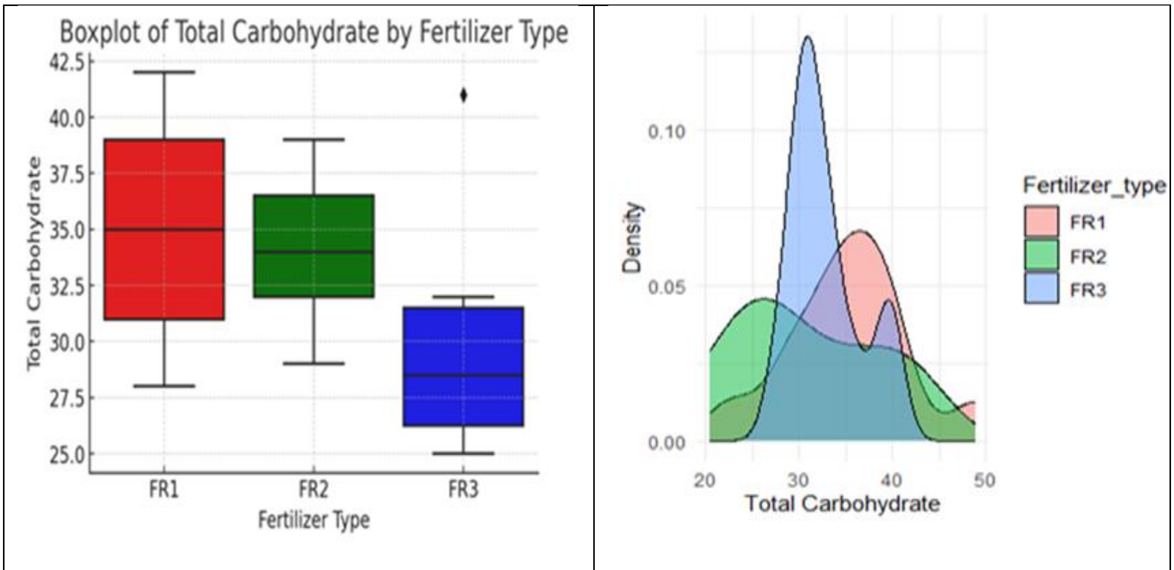
3.1.2 Total carbohydrate

Table 10: ANOVA summary of total carbohydrate

	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Potting media	2	71.8	35.90	2.519	0.1016
Fertilizer type	2	113.8	56.90	3.993	0.0319 *
Potting media: Fertilizer type	4	38.5	9.63	0.676	0.6152
Residuals	24	342.0	14.25		

The total carbohydrate content of the vegetables was significantly affected by fertilizer type ($p<0.05$), indicating that nutrient input plays a substantial role in modulating carbohydrate metabolism and accumulation in leafy vegetables. This outcome suggests that the availability and composition of macronutrients, particularly nitrogen and potassium in different fertilizer treatments likely influence photosynthetic efficiency and carbohydrate biosynthesis.

In contrast, neither the growth media composition ($p = 0.102$) nor the interaction between fertilizer type and media ($p = 0.615$) exerted a statistically significant effect on carbohydrate levels. These results imply that while fertilization directly enhances carbohydrate accumulation, the physicochemical properties of the soilless substrates used in this study may not have provided additional influence. It is therefore plausible that carbohydrate content is more sensitive to nutrient availability than to the characteristics of the substrate in soilless cultivation systems.



(a)Boxplot (b) Density plot

Figure 9: Total carbohydrates content in leafy vegetables across different fertilizer types

Figure 9 (a) and (b) illustrate the effect of fertilizer type on total carbohydrate content in leafy vegetables. The highest carbohydrate levels were observed in vegetables grown with organic fertilizer (FR1). Plants treated with NPK (FR2) fertilizer showed moderate carbohydrate content, while the lowest levels were recorded in the unfertilized control group. The limited availability of essential nutrients in the soilless medium composed of charcoal dust or coffee husks, may have restricted carbohydrate synthesis. The density plot further supports the observation that fertilizer type influences carbohydrate accumulation, with both organic and NPK fertilizers leading to broader distributions and generally higher carbohydrate content compared to the no-fertilizer treatment.

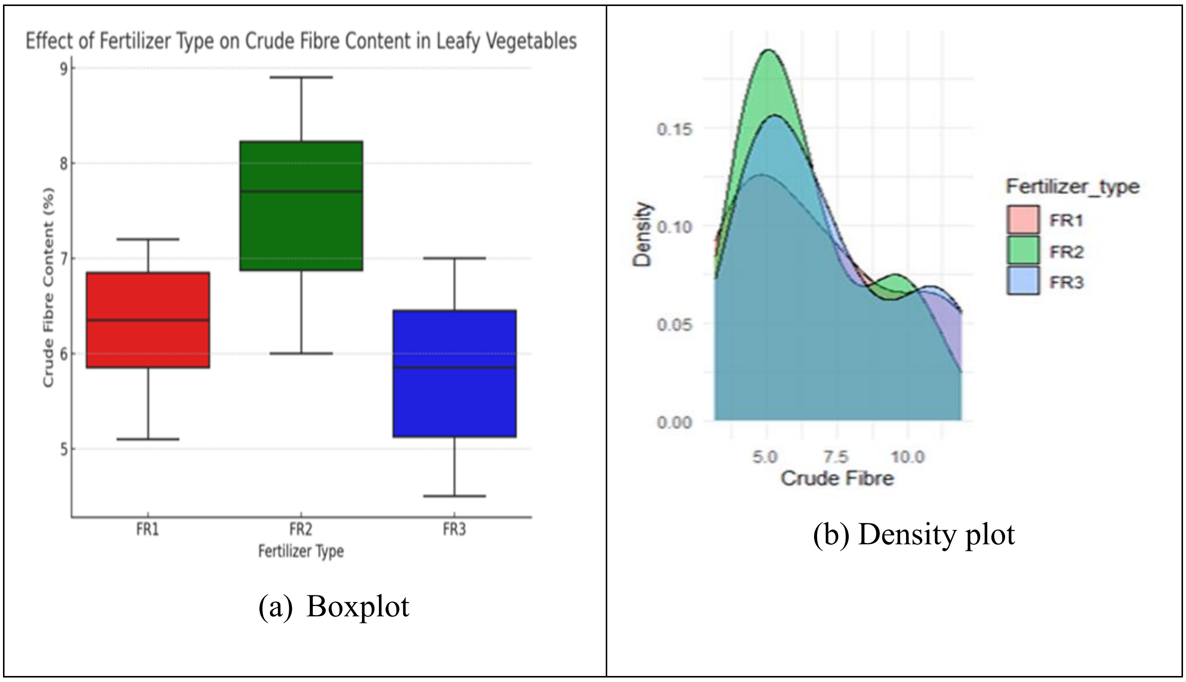
3.1.3 Crude fibre

Table 11: ANOVA summary

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Potting media	2	1.989	0.9946	3.389	0.0505
Fertilizer type	2	2.223	1.1116	3.788	0.0372 *
Potting media : Fertilizer type	4	0.999	0.2496	0.851	0.05073
Residuals	24	7.043	0.2935		

Fertilizer type also had a significant effect on crude fiber content (*p* <0.05), indicating that different fertilizers influence cell wall development and fiber accumulation in leafy vegetables. Growth media showed a near-significant effect (p = 0.0505), suggesting a possible influence on fiber accumulation, although this was not statistically conclusive at the 0.05

threshold. The interaction between growth media and fertilizer type was not significant (p = 0.5073).



(a) Boxplot

(b) Density plot

Figure 10: Crude fibre content in leafy vegetables across different fertilizer types

Figure 10 (a) and (b) illustrate the impact of fertilizer type on the crude fibre content of leafy vegetables. The highest crude fibre levels were observed in plants treated with (FR2) NPK fertilizer, followed by those grown with (FR1) organic fertilizer, which showed moderate levels. The lowest crude fibre content was recorded in vegetables grown without any fertilizer application.

3.1.4 Dry matter, Crude Fat, Total Ash

Table 12: Summary of statistically non-significant experimental factors in leafy vegetables nutrient

Dry matter

	Df	SumSq	MeanSQ	F value	Pr(>F)
Growth media	2	2.71	1.357	0.484	0.622
Fertilizer type	2	12.59	6.296	2.247	0.128
Growth media: Fertilizer type	4	4.60	1.150	0.410	0.800
Residuals	24	67.26	2.803		

(P>0.05)

Total Ash

	Df	SumSq	MeanSQ	F value	Pr(>F)
Growth media	2	35.35	17.673	1.546	0.234
Fertilizer type	2	30.24	15.122	1.323	0.285
Growth media: Fertilizer type	4	20.95	5.237	0.458	0.766
Residuals	24	274.34	11.431		

(P>0.05)

Crude Fat

	Df	SumSq	MeanSQ	F value	Pr(>F)
Growth media	2	3.46	1.732	1.157	0.331
Fertilizer type	2	1.27	0.636	0.425	0.659
Growth media: Fertilizer type	4	2.71	0.677	0.452	0.770
Residuals	24	35.93	1.497		

(P>0.05)

Overall, the results show that differences in the types of growth media and fertilizer had no significant impact on dry matter, crude fat and total ash content in leafy vegetables. This implies that these nutrient characteristics may be more heavily influenced by other variables, such as genetic variability, environmental circumstances, or nutrient interactions.

3.2 Discussion

3.2.1. Vegetable yield under soilless growth media with application different fertilizers types

The enrichment of soilless media with organic and inorganic fertilizers influenced the yield performance of the selected leafy vegetables, with outcomes shaped by both substrate composition and crop-specific nutrient physiology.

Spinach, a nitrate-responsive species with high-affinity root transporters, benefited from the enhanced aeration and ionic availability in GM3 when enriched with NPK (FR2). This combination facilitated efficient nitrate uptake, Rubisco activation, and carbon assimilation, consistent with findings by (Michelon et al., 2021). The marginal yield difference between FR2 and the control suggests spinach's partial nitrogen autonomy in well-aerated substrates (Ayodele et al., 2010). Organic fertilizer, while beneficial for chlorophyll synthesis, underperformed in denser media due to nitrogen immobilization and short-lived ammonium deficits. The control treatment demonstrated spinach's partial nitrogen independence in aerated systems, though with a modest 1–2% yield reduction. These findings align with optimal EC thresholds (~1.2 dS m^{-1}) for maximizing stomatal conductance without salinity stress (Ayodele et al., 2010; Michelon et al., 2021).

Cowpea greens, a leguminous crop, responded best to organic enrichment (FR1) in GM2. The balanced media supported rhizobial symbiosis and phosphorus mobilization, enhancing biological nitrogen fixation and dry matter accumulation (Adekayode & Ogunkoya, 2011). In contrast, NPK in denser media suppressed nodulation due to ethylene-mediated inhibition under anaerobic conditions, reducing nitrogen fixation and dry matter accumulation. The control in 1:2 media leveraged residual phosphorus but lacked sufficient nitrogen supplementation. These outcomes emphasize cowpea's nitrogen-sparing physiology and the effectiveness of organic inputs in sustaining yield and soil organic matter (Adekayode & Ogunkoya, 2011; Ojo et al., 2010).

Amaranth exhibited resilience across treatments, with slightly higher yields under FR1 in GM3. Organic fertilizer in aerated media enhanced phosphorus solubilization and nitrogen mineralization, facilitated by humic substances that stimulated proton-ATPase activity and root proliferation. NPK, while increasing tissue nitrogen, suffered from leaching in low-CEC substrates, leading to short-lived nitrate surges without sustained biomass gains. The control's near-equivalent yield highlights amaranth's adaptability to low-input systems and its efficient use of residual phosphorus. Organic inputs also correlated with improved nutritional quality (e.g., vitamin C) and soil fertility, reinforcing their role in sustainable amaranth cultivation (Ayodele et al., 2010; Paul et al., 2024).

Collard, a nitrogen-intensive Brassica, showed optimal performance under FR2 in GM2, where balanced nutrient ratios and aeration supported high photosynthetic rates. However, the narrow yield margin between FR2 and FR1 suggests that organic inputs may also sustain productivity while enhancing nutritional quality (Qureshi et al., 2022). The control maintained moderate yields via residual fertility but experienced nutrient dilution effects. These findings advocate for integrated fertilization strategies to balance yield and nutritional quality in Brassica crops under soilless conditions (Qureshi et al., 2022; Michelon, et al., 2021).

The enrichment of soilless media with organic and inorganic fertilizers significantly influenced the yield performance of selected leafy vegetables, with outcomes shaped by both substrate composition and crop-specific nutrient physiology. Spinach and collard demonstrated optimal productivity in inert-dominant media enriched with NPK, leveraging rapid nitrate uptake and enhanced photosynthetic efficiency. In contrast, cowpea greens and amaranth responded more favorably to organic amendments in balanced media, benefiting from microbial symbioses and phosphorus mobilization. These results affirm that fertilizer enrichment strategies must be crop-specific and media-sensitive to optimize yield, nutrient use efficiency, and sustainability in semi-arid horticultural systems.

Yield response to growth media and fertilizer treatments

The two-way ANOVA results indicated that growth media regime, fertilizer type, and their interaction did not significantly influence yield across the four leafy vegetables ($p > 0.05$). This suggests that the tested treatments did not produce statistically distinguishable effects on productivity. However, vegetable type emerged as a major source of variation, with spinach consistently yielding higher (up to 7.524 $t \cdot ha^{-1}$) than collard, cowpea, and amaranth. These findings imply that inherent crop characteristics play a more dominant role in determining yield than the applied media or fertilizer combinations. Despite the lack of statistical significance, observed trends showed that GM3 (1:2) combined with NPK fertilizer tended to support slightly higher yields in spinach and amaranth, indicating potential agronomic value worth exploring in future trials.

Although growth media and fertilizer regimes did not significantly influence yield, the observed species differences and slight trends under GM3 with NPK fertilizer provide useful guidance for practice. For farmers, this suggests that investing heavily in specific media or fertilizer combinations may not guarantee higher yields across all leafy vegetables. Instead, focusing on crop choice particularly spinach, which consistently outperformed the others offers a more reliable pathway to improved productivity. At the same time, the comparable performance of organic fertilizer treatments highlights opportunities for integrating organic inputs to reduce costs and enhance soil fertility. From a policy perspective, these findings support initiatives that promote balanced nutrient management strategies, combining organic amendments with judicious use of inorganic fertilizers. Such approaches align with Uganda's broader goals of sustainable agricultural intensification, ensuring that productivity gains are achieved without compromising long-term soil health or farmer livelihoods. Overall, yield performance was driven more by crop species than by growth media or fertilizer regime, underscoring the importance of crop choice and balanced nutrient management for sustainable vegetable production in Uganda

3.2.2 Nutrient profiles of leafy vegetables

Crude Protein

Crude protein content was significantly influenced by fertilizer type, whereas growth media and the interaction between both factors did not show statistically significant effects. This suggests that nitrogen availability, often determined by fertilizer composition and rate of application, is a key factor in protein synthesis in leafy vegetables (Kunkulberga et al., 2019; Wang et al., 2023; Wang et al., 2021). Adequate nitrogen levels enhance the nutritional quality of leafy vegetables by promoting the synthesis of amino acids, the fundamental building blocks of proteins.

Balanced fertilization strategies ensure that plants receive the nutrients necessary for optimal growth and protein production (Maheswari et al., 2017a; Wan et al., 2023). According to Farhan et al., (2024), the use of nitrogen-rich fertilizers significantly increases protein content in green crops. Integrated nutrient management further improves nitrogen use efficiency (NUE) and protein synthesis. Swanson et al., (2022) also reported that different fertilization regimes can affect the nutrient profile of leafy greens, including their protein content.

These findings are consistent with those of Grobelnik Mlakar (2012), who noted that nitrogen fertilization significantly boosts protein levels in amaranth enhancing amino acid biosynthesis and nitrogen assimilation. Similarly, Shaji et al. (2021) found that organic fertilizers can promote protein accumulation in leafy greens due to their slow-release nitrogen properties, which improve nutrient uptake over time.

Interestingly, green vegetables grown in soilless media exhibited higher crude protein content, likely due to the enhanced bioavailability of nitrogen from both organic and inorganic fertilizers. Unlike soil-based systems, soilless media offer direct access to nutrients, with minimal microbial immobilization or competition with soil particles (Liu et al., 2024). According to Dion et al. (2020), organic fertilizers release nitrogen gradually, improving long-term uptake efficiency, while inorganic fertilizers provide immediate nitrogen availability, supporting rapid protein synthesis.

Moreover, optimal aeration and root-zone hydration in soilless systems further facilitate nutrient absorption and stimulate the biosynthesis of proteins and amino acids. Fertilizers, particularly nitrogen-rich ones, play a direct role in protein production, as nitrogen is a primary component of amino acids. Therefore, the observed increase in crude protein content likely reflects the sufficient nitrogen supply provided by the fertilizers, which in turn enhanced protein biosynthesis pathways in the leafy vegetables (Maheswari et al., 2017b).

Total Carbohydrate

The results showed that fertilizer type had a significant effect on total carbohydrate content, whereas growth media and the interaction between the two factors were not statistically significant. This suggests that the type of fertilizer plays a key role in carbohydrate accumulation, likely by influencing photosynthesis and energy storage processes (Si et al., 2018). These findings are consistent with those of Feng et al. (2024a), who reported that nitrogen-rich fertilizers enhance carbohydrate synthesis by increasing chlorophyll content and improving photosynthetic efficiency. Balanced fertilization strategies also contribute to optimized carbohydrate levels in leafy vegetables, which directly affect product quality and consumer preference (Chen et al., 2021; Guo et al., 2022).

The highest total carbohydrate content was observed in vegetables treated with organic fertilizer. This may be attributed to the gradual release of nutrients from organic matter, which sustains photosynthesis and carbohydrate accumulation over time (Martínez-Alcántara et al., 2016). The enhanced availability of micronutrients from organic fertilizers also supports enzymatic processes involved in carbohydrate biosynthesis. Fertilizers that enhance photosynthetic capacity and energy metabolism tend to promote carbohydrate accumulation, as reflected in the present results. The observed increase in carbohydrate content likely reflects improved photosynthetic activity due to optimized nutrient availability (Wei et al., 2024).

Moreover, balanced fertilizer application ensures that plants have access to essential nutrients for healthy growth and development, leading to higher-quality products that meet consumers' expectations (Gao et al., 2020). In addition to improving product quality, this approach supports sustainable agricultural practices by preserving soil health and reducing dependence on excessive chemical inputs.

The increase in total carbohydrates observed in soilless systems may also be attributed to enhanced photosynthetic efficiency. The absence of compacted soil layers in these media improves root oxygenation, facilitating greater carbon assimilation and starch accumulation in leaves (Liu et al., 2024). Organic fertilizers further stimulate beneficial microbial activity, promoting nutrient solubilization and uptake, thereby supporting sustained carbohydrate production. The controlled nutrient delivery in soilless systems minimizes plant stress and contributes to higher glucose reserves.

Crude Fibre

Crude fiber content was significantly influenced by fertilizer type, while growth media showed marginal significance ($p = 0.0505$), and the interaction effect was not significant. These results suggest that nutrient management strategies play a key role in fiber accumulation, likely due to their influence on cell wall formation and the structural integrity of plant tissues. The highest crude fiber content was observed in plants treated with NPK fertilizer, likely due to the rapid availability of nutrients, particularly nitrogen, which promotes cell wall development and fiber biosynthesis (Wang et al., 2023). The variability in fiber content indicates a differing response based on nutrient uptake efficiency.

Crude fiber, which includes cellulose, hemicellulose, and lignin, is closely linked to structural development in plants. Fertilizers that enhance vegetative growth and cell wall thickening tend to increase fiber accumulation, suggesting that the treatments supported the development of robust leaf tissue (Echer et al., 2020).

Panta & Parajulee (2021) emphasized that integrated nutrient management not only improves crop yields but also enhances soil quality and reduces greenhouse gas emissions, indirectly supporting fiber accumulation. Similarly, Pedreira et al. (2023) showed that effective nutrient strategies in forage crops improve both structural integrity and nutritive value. Furthermore, Batabyal (2017) highlighted the importance of nutrient management in improving crop quality and sustaining soil health, underscoring its role in the formation and maintenance of plant tissues. Adequate nitrogen and potassium fertilization was also found to enhance lignin and cellulose synthesis, thereby promoting fiber development (Pedreira et al. 2023). Batabyal (2017) further noted that controlled nutrient supply encourages optimal fiber accumulation without compromising leaf tenderness and quality. Organic manure supports moderate fiber accumulation, without compromising leaf tenderness.

Organic fertilizers contributed to moderate fiber accumulation, helping maintain desirable texture in leafy vegetables. Their slow decomposition provides a steady nutrient release, promoting balanced growth and structural quality.

In contrast, nutrient deficiency due to lack of fertilization can lead to thicker cell walls as a plant defense mechanism, resulting in increased crude fiber content (Li et al., 2024). Soilless media may further influence fiber accumulation by improving water and nutrient retention, reducing drought stress, and enhancing cell wall thickness and more fiber synthesis. Moreover, precise nutrient management in soilless systems ensures optimal availability of key minerals such as calcium and potassium, both essential for fiber formation and structural reinforcement (Li et al., 2024; Schwarz et al., 2009). While organic fertilizers stimulate the production of secondary metabolites, inorganic sources directly supply minerals crucial for cell wall integrity and fiber content (Association of Official Analytical Chemists, 2000).

Crude Fat

Leafy vegetables are inherently low in fat, as their primary metabolic focus is directed toward carbohydrate and protein production rather than lipid biosynthesis (Inyang, 2016). The absence of a significant effect of fertilizer type on crude fat content suggests that fat accumulation in these vegetables is largely genetically determined and not strongly influenced by external nutrient availability (Sossa-Vihotogbe et al., 2013).

Unlike oil-rich crops such as avocados or nuts, leafy vegetables typically contain low levels of lipids, most of which are structural phospholipids rather than storage fats. These phospholipids, essential components of cell membranes, are not notably affected by fertilization (Breve et al., 2023). In contrast to oilseed crops, where nitrogen and phosphorus supplementation can enhance lipid synthesis, leafy vegetables lack an efficient carbon-to-lipid conversion pathway. As a result, fertilizer application has little to no impact on fat formation in these species (Vidal et al., 2018).

Moreover, since lipid metabolism is predominantly controlled by genetic factors, the growth medium, whether soil-based or soilless (e.g., charcoal and coffee husks), is unlikely to significantly influence fat content. The findings from this study reaffirm the status of leafy vegetables as naturally low-fat foods, whose lipid levels remain stable regardless of fertilization. This stability supports their role in heart-healthy diets.

Similarly, a study by Hossain & Ryu (2018) on lettuce (*Lactuca sativa* L.) found that although both organic and inorganic fertilizers improved growth parameters and nutrient uptake, they did not significantly affect the lipid content of the leaves. These findings are consistent with the present results, confirming that crude fat levels in leafy vegetables are relatively unaffected by fertilizer type.

Dry Matter

Dry matter, which represents the total solid content of vegetables excluding water, is closely associated with plant structure and biomass accumulation (Szulc et al., 2021). In this study, the absence of a significant effect of fertilizer type on dry matter content suggests that plants maintained similar water and solid content regardless of nutrient input. This may indicate that the water retention capacity of the soilless medium outweighed any potential influence of fertilizer on dry matter accumulation (Fidler & Gómez, 2025).

Rather than contributing to structural biomass, nutrient uptake might have been redirected toward metabolic processes such as protein and carbohydrate synthesis. The soilless medium's composition of coffee husks and charcoal probably offered enough water availability and aeration to keep the dry matter content constant throughout the treatments. The stability of these parameters across fertilizer treatments indicates that they are less sensitive to fertilizer type and are more likely determined by plant genetics and environmental factors. This could imply that nutrient uptake and mineral deposition are regulated to maintain homeostasis within the plant, regardless of external inputs (Peng et al., 2016).

The differential effects of fertilizers on various nutritional traits highlight the selective influence of external nutrient inputs on plant metabolism. While fertilizer application can enhance energy-dependent processes such as protein synthesis, carbohydrate accumulation, and vegetative growth, parameters like crude fat, ash, and dry matter content appear to be more genetically or environmentally regulated (Feng et al., 2024b). This underscores the importance of designing fertilizer strategies tailored to the desired nutritional outcomes in leafy vegetables.

In soilless cultivation systems, the stability of dry matter content also suggests that fertilizer type is unlikely to significantly affect post-harvest quality traits such as dehydration rate or processing performance. Since dry matter is directly related to shelf life and storage stability, its consistency across treatments is a valuable attribute in the context of post-harvest handling (Luna et al., 2013).

Total Ash

Ash content represents the total mineral composition of the plant, including essential elements such as calcium, potassium, and magnesium, as well as trace minerals. The lack of significant differences among treatments suggests that the soilless growth media composed of charcoal and coffee husks may have already provided sufficient baseline mineral levels, thereby reducing the observable impact of additional fertilizer application (Kiggundu et Sittamukyoto, 2019).

Moreover, mineral accumulation in leafy vegetables is often genetically regulated, meaning that uptake may not increase significantly beyond a certain threshold, even when nutrient availability rises (Rashid et al., 2022). Some minerals are also relatively immobile within plants, and if already present in adequate quantities, their uptake may not respond noticeably to external fertilization.

This finding highlights that excessive use of fertilizers, particularly inorganic types, may not enhance mineral accumulation and could instead lead to unnecessary input costs and potential environmental leaching, without providing additional nutritional benefits to the crop (Bisht et Singh Chauhan, 2021; Liu et al., 2021).

The markedly low ash content (14.00 %) observed in cowpea under GM1 + FR2 relative to other treatments can be attributed to the interaction between potting media composition and NPK fertilization. Ash content reflects the total mineral residue after combustion, and its reduction suggests limited mineral accumulation in plant tissues. In the GM1 medium (2:1 charcoal dust: coffee husks), the substrate may have provided a relatively inert environment with reduced mineral availability. When combined with NPK fertilizer, which primarily supplies macronutrients (N, P, K), the uptake of secondary and micronutrients such as calcium, magnesium, and trace elements may have been suppressed. This phenomenon aligns with the concept of nutrient antagonism, where excess macronutrients interfere with the absorption of other essential minerals, thereby lowering total ash content (Rietra et al., 2017).

The dilution effect further explains the reduced ash concentration under GM1 + FR2. NPK fertilization is known to stimulate vigorous vegetative growth and protein accumulation, as reflected in the high crude protein value (24.31%) for this treatment. However, rapid biomass expansion often dilutes mineral concentrations within tissues, leading to lower ash percentages (Imo, 2012). Thus, the combination of GM1 medium and NPK fertilizer likely promoted biomass accumulation at the expense of mineral density, resulting in the lowest ash content among treatments.

Finally, the specific chemical properties of the GM1 substrate may have compounded the effect. Charcoal dust, while improving soil aeration, has limited inherent mineral content, and coffee husks, though organic, release nutrients slowly. This substrate composition may have restricted the mineral pool available for uptake, especially under conditions of high nutrient demand induced by NPK fertilization. Studies on cowpea nutrient dynamics confirm that substrate fertility and fertilizer type strongly influence mineral deposition in tissues, with imbalanced nutrient supply leading to reduced ash values (Bondok et al., 2024a). Therefore, the low ash content in GM1 + FR2 reflects a combined effect of substrate limitations, nutrient antagonism, and dilution, highlighting the importance of balanced fertilization strategies to sustain both yield and mineral density.

Iron

Micronutrient density in legumes is strongly influenced by fertilization practices, and the present study highlights two mechanisms that explain the elevated iron concentrations observed in cowpea under control treatments (e.g., GM1 + FR3 = 0.05 mg/100 g; GM2 + FR3 = 0.03 mg/100 g). First, the dilution effect accounts for reduced iron concentrations in fertilized plants, as nutrient inputs whether organic or inorganic stimulate vigorous vegetative growth and protein accumulation, thereby increasing total biomass but lowering the relative concentration of micronutrients such as iron. In unfertilized plants, limited biomass production results in higher iron concentration per unit dry matter, a phenomenon documented in cowpea and other legumes where increased yields under fertilization corresponded with reduced micronutrient density in edible tissues (Britz et al., 2023; Kiran et al., 2018). Second, the absence of nutrient antagonism under control conditions may enhance iron uptake, since fertilizer-derived ions, particularly phosphorus and potassium, can interfere with iron absorption at the root–soil interface. Without these competing ions, cowpea roots may mobilize iron more effectively through rhizosphere acidification and organic exudates, a stress-adaptive strategy observed in biofortification studies (North-West University et al., 2020)**.**Taken together, these findings underscore a critical trade-off: while fertilization improves yield, it may compromise nutritional quality. This duality poses a challenge for sustainable agricultural systems, where strategies must balance productivity with micronutrient density to meet both commercial and nutritional demands (Villagran et al., 2025)

The observed differences in crop nutritive profiles between mineral and organic fertilizer treatments may be explained by the contrasting nutrient release dynamics. Unlike mineral fertilizers, where nutrient additions are precisely defined and standardized, the nutrient input from organic fertilizers is inherently variable and dependent on source material and decomposition dynamics. This variability may have influenced the final results, as organic amendments such as *Tithonia diversifolia* supplied nitrogen and other nutrients in less predictable but more gradually available forms compared to the immediate and well-quantified inputs from mineral fertilizers. Consequently, the observed differences can be attributed not only to the quantity of nutrients supplied but also to the contrasting release patterns and biological interactions associated with organic versus mineral fertilization.

3.3 Comparative analysis of nutrient profiles of selected leafy vegetables grown in soilless systems versus soil-based agronomy

Table 13 Nutrient composition of soil-grown leafy vegetables under organic and inorganic fertilizer treatments.

Vegetable	Treatment	Dry Matter (%)	Ash (%)	Crude Fat (%)	Crude Fiber (%)	Crude Protein (%)	Carbohydrates (%)	Iron (mg/g)	Source
Spinach	Organic	90–93	22–24	5.1–6.2	6.5–7.9	20–22	28–30	0.021–0.033	Moorthi S., 2023; Sudharani et al., 2024; Amos et al., 2023
	Inorganic	88–91	20–23	4.5–5.8	6.3–7.2	18–20	26–28	0.018–0.028	Amos et al., 2023
Cowpea	Organic	82–85	19–22	2.8–3.5	9.2–10.6	23–25	22–25	0.020–0.027	Affrifah et al., 2022; Devisetti & Prakash, 2020; Oke et al., 2021
	Inorganic	80–83	18–21	2.7–3.1	9.0–10.1	22–24	21–24	0.018–0.024	Oke et al., 2021
Amaranth	Organic	88–91	11–13	8.5–10.2	3.4–4.6	22–24	42–45	0.024–0.035	Soriano-García & Aguirre-Díaz, 2020; Bowen University et al., 2022; Botanical online, 2024
	Inorganic	86–89	10–12	8.0–9.4	3.2–4.1	21–23	40–43	0.021–0.030	Bowen University et al., 2022
Collard	Organic	88–91	14–16	8.1–9.0	4.8–5.4	26–28	31–35	0.012–0.020	Canazza et al., 2024b
	Inorganic	86–89	13–15	7.5–8.8	4.7–5.2	25–27	30–34	0.011–0.018	WHFoods, 2025; Nutrition value org., 2024

All values are expressed per 100g dry weight. Ranges reflect variability across studies.

3.3.1 Spinach

Table 14: Spinach nutrient comparison: soil-based versus soilless systems

Fertilizer type	system	Dry matter (%)	Total ash (%)	Crude fiber (%)	Crude fat (%)	Crude Protein (%)	Total carbohydrate (%)	Iron (mg/g)
Organic	Soil-based	90–93	22–24	6.5–7.9	5.1–6.2	20–22	28–30	0.021–0.033
Organic	Soilless	92.76	25.08	7.51	7.83	22.47	29.86	0.023
NPK	Soil-based	88–91	20–23	6.3–7.2	4.5–5.8	18–20	26–28	0.018–0.028
NPK	Soilless	93.20	24.71	6.49	9.15	27.03	25.83	0.026
Control	Soilless	92.92	23.97	7.26	7.21	23.79	30.69	0.020
Control	Soil-based	~89.5	~22	~7.0	~5.5	~19.5	~27	~0.025

A comparative analysis of spinach (Table 15) key observations:

Dry Matter & Ash: Soilless spinach consistently shows slightly higher dry matter and ash content across all treatments, suggesting more concentrated nutrient retention.

Crude Fat & Protein: NPK-treated soilless spinach has notably higher fat (9.15%) and protein (27.03%) compared to its soil-based counterpart.

Carbohydrates: Control treatment in soilless systems yields the highest carbohydrate content (30.69%), slightly above soil-based values.

Iron: Iron levels are comparable across systems, though NPK soilless spinach shows a modest increase.

Soilless systems, especially under NPK and control treatments, enhance certain nutrient concentrations, particularly protein and fat, while maintaining comparable fiber and iron levels. Organic soilless spinach also performs well, showing balanced improvements across most parameters.

3.3.2 Cowpea

A comparative analysis of cowpea (Table 16) key observations:

Dry Matter: Soilless cowpea shows slightly higher dry matter content under organic and control treatments, suggesting strong support for bulk biomass production and dietary health components.

Crude Fibre: Soilless cowpea consistently has higher fibre levels, especially under organic and control treatments.

Crude Protein: NPK-treated soilless cowpea (25.19%) exceeds soil-based values, indicating enhanced protein synthesis.

Carbohydrates: Organic and control soilless cowpea show higher carbohydrate content than their soil-based counterparts. On the other hand, carbohydrate levels were notably lower under NPK treatments, hinting that chemical fertilizers may shift metabolic pathways toward protein and fat synthesis at the expense of sugar storage.

Iron: Control treatment in soilless cowpea (0.03 mg g^{-1}) is at the upper end of soil-based iron ranges.

Soilless systems, particularly under NPK and control treatments, enhance cowpea's protein, fibre, and iron content. Soil-based systems still perform well, especially under organic treatment, but tend to show slightly lower nutrient density overall.

Table 15: Cowpea nutrient composition: soilless versus soil-based systems

Fertilizer Type	System	Dry Matter (%)	Total Ash (%)	Crude Fibre (%)	Crude Fat (%)	Crude Protein (%)	Carbohydrates (%)	Iron (mg/g)
Organic	Soilless	86.19	21.64	11.18	2.74	19.63	31.00	0.02
Organic	Soil-Based	82–85	19–22	9.2–10.6	2.8–3.5	23–25	22–25	0.020–0.027
NPK	Soilless	82.38	20.92	9.90	2.95	25.19	23.93	0.02
NPK	Soil-Based	80–83	18–21	9.0–10.1	2.7–3.1	22–24	21–24	0.018–0.024
Control	Soilless	84.32	22.97	11.04	2.65	17.34	30.66	0.03
Control	Soil-Based	~82–85	~21–24	~10–12	~2.5–3.2	~17–20	~28–32	~0.02–0.05

3.2.3 Amaranth

Table 16: Amaranth nutrient composition: soilless versus soil-based systems

Fertilizer type	System	Dry Matter (%)	Ash (%)	Crude Fat (%)	Crude Fibre (%)	Crude Protein (%)	Carbohydrates (%)	Iron (mg/g)
Organic	Soilless	89.97	12.59	9.03	3.74	23.42	42.53	0.03
NPK	Soilless	89.96	12.04	8.04	4.42	25.06	39.49	0.02
Control	Soilless	89.92	14.71	8.74	4.72	24.18	37.57	0.01
Organic	Soil-Based	88–91	11–13	8.5–10.2	3.4–4.6	22–24	42–45	0.024–0.035
Inorganic	Soil-Based	86–89	10–12	8.0–9.4	3.2–4.1	21–23	40–43	0.021–0.030

A comparative analysis of amaranth grown under soilless and soil-based (Table 17) systems reveals distinct differences in nutrient composition:

Dry Matter: Soilless treatments maintain consistent dry matter (~89.9%), while soil-based systems show greater variability (86–91%).

Ash Content: Soilless-grown amaranth exhibits higher ash levels, especially in the control treatment (14.71%), indicating increased mineral accumulation. Soil-based samples range from 10–13%.

Crude Fat: Fat content is slightly higher in soil-based systems (up to 10.2%), though soilless treatments also show substantial values (8.04–9.03%).

Crude Fibre: Fibre is more pronounced in soilless-grown amaranth, particularly in the control (4.72%), compared to soil-based samples (3.2–4.6%).

Crude Protein: Soilless cultivation supports higher protein levels (23.42–25.06%), while soil-based treatments range from 21–24%.

Carbohydrates: Soil-based amaranth contains more carbohydrates (40–45%), whereas soilless samples are slightly lower (37.57–42.53%).

Iron Content: Iron is more abundant in soil-based treatments (0.021–0.035 mg/g), with soilless systems showing reduced levels (0.01–0.03 mg/g).

This summary highlights how cultivation method influences the nutritional profile of amaranth, with soilless systems favoring protein and fibre, and soil-based systems enhancing carbohydrate and iron content.

3.3.4 Collard

Table 17: Collard nutrient composition: soilless versus Soil-based systems

Fertilizer type	System	Dry Matter (%)	Ash (%)	Crude Fat (%)	Crude Fibre (%)	Crude Protein (%)	Carbohydrates (%)	Iron (mg/g)
Organic	Soilless	89.97	12.59	9.03	3.74	23.42	42.53	0.03
NPK	Soilless	89.96	12.04	8.04	4.42	25.06	39.49	0.02
Control	Soilless	89.92	14.71	8.74	4.72	24.18	37.57	0.01
Organic	Soil-Based	88–91	14–16	8.1–9.0	4.8–5.4	26–28	31–35	0.012–0.020
NPK	Soil-Based	86–89	13–15	7.5–8.8	4.7–5.2	25–27	30–34	0.011–0.018

Table 18 shows a comparative evaluation of the proximate and mineral composition of collard grown under soilless and soil-based cultivation systems, with emphasis on organic, inorganic

(NPK), and control treatments. The findings reveal distinct trends in nutrient accumulation influenced by the growing medium and fertilizer type.

Dry Matter Content: Soilless treatments exhibited a narrow and consistent range of dry matter values, averaging approximately 89.9%. In contrast, soil-based treatments demonstrated greater variability, ranging from 86% to 91%. This suggests that environmental factors inherent to soil systems may contribute to fluctuations in moisture retention and biomass accumulation.

Total Ash Content: Ash content, indicative of total mineral presence, ranged from 12.04% to 14.71% in soilless systems, with the control treatment (FR3) recording the highest value. Soil-based treatments showed slightly elevated ash levels overall (13–16%), particularly under organic fertilization, implying enhanced mineral uptake from naturally enriched substrates.

Crude Fat Content: Fat content in soilless-grown collard ranged between 8.04% and 9.03%, marginally higher than soil-based counterparts (7.5–9.0%). Although the ranges overlap, the elevated fat levels in soilless systems may reflect optimized nutrient delivery and reduced competition for resources.

Crude Fibre Content: Crude fibre was more pronounced in soil-based treatments, especially under organic fertilization (4.8–5.4%), compared to 3.74–4.72% in soilless systems. This suggests that soil environments may better support structural carbohydrate synthesis, possibly due to microbial interactions and root zone complexity.

Crude Protein Content: Protein content was notably higher in soil-based collard, ranging from 25% to 28%, with organic treatments leading. Soilless systems yielded slightly lower values (23.42–25.06%), though still substantial. The superior protein levels in soil-grown plants may be attributed to enhanced nitrogen mineralization and microbial activity.

Carbohydrate Content: Soilless-grown collard demonstrated significantly higher carbohydrate concentrations (37.57–42.53%) compared to soil-based treatments (30–35%). This inverse relationship with protein suggests a metabolic trade-off, where soilless systems may favor energy storage over amino acid synthesis.

Iron Content: Iron levels were modestly higher in soil-based treatments (0.011–0.020 mg/g), particularly under organic fertilization, while soilless systems ranged from 0.01 to 0.03 mg/g. The mineral-rich nature of soil and its buffering capacity likely contribute to improved micronutrient availability.

The comparative data underscore the influence of cultivation systems on the nutritional profile of collard. While soilless systems offer consistency and enhanced carbohydrate accumulation, soil-based systems, especially those utilizing organic inputs, support superior protein, fibre, and mineral content. These findings have implications for targeted nutritional outcomes in crop production and may inform best practices for sustainable agriculture.

3.4. Discussion

3.4.1. Spinach (*Spinacia oleracea* L.)

Recent studies have shown that cultivation under soilless conditions with NPK fertilizers can significantly enhance these attributes. For instance, (Moorthi & D’Souza, 2025) reported that spinach grown hydroponically with balanced NPK inputs exhibited elevated crude protein levels (up to 22.47%), alongside increased fat and iron concentrations compared to soil-grown counterparts. This improvement is attributed to the precise nutrient delivery and reduced competition in soilless systems, which promote efficient uptake and metabolic allocation toward energy-dense compounds (Tuxun et al., 2025).

Conversely, spinach cultivated in soil-based systems with organic fertilizers tends to accumulate higher levels of crude fiber and ash. Organic inputs such as compost and farmyard manure enrich the soil with microbial activity and slow-release nutrients, which stimulate structural growth and mineral retention in plants (Hashimi et al., 2019). These conditions favor the synthesis of cell wall components and the uptake of trace minerals, resulting in higher fiber content and total ash values. Such findings underscore the role of soil ecology and organic matter in shaping the nutritional architecture of leafy vegetables (Jaya & Prased, 2014).

The contrast between soilless NPK and soil-based organic systems highlights a synergistic relationship between cultivation medium and nutrient source. While soilless systems optimize nutrient precision and metabolic efficiency, soil-based environments offer complex biological interactions that support mineral diversity and structural integrity. This duality suggests that tailoring fertilizer strategies to specific nutritional goals, such as protein enhancement or fiber enrichment, can improve the functional value of spinach and other leafy greens (Hashimi et al., 2019; Jaya & Prased, 2014; Moorthi & D'Souza, 2025).

Spinach's nutritional composition is highly sensitive to environmental factors, including light intensity, temperature, and nutrient availability. Under controlled soilless conditions, these variables can be optimized to enhance phytochemical accumulation. For example, hydroponic systems supplemented with NPK fertilizers have been shown to increase chlorophyll and carotenoid content, contributing to improved antioxidant capacity (Kumar et al., 2024; Tuxun et al., 2025). These bioactive compounds not only enhance the health benefits of spinach but also improve its visual appeal and shelf life. Moreover, the absence of soil-borne pathogens in soilless cultivation reduces stress-induced metabolic shifts, allowing the plant to allocate more resources toward nutrient synthesis (Othman et al., 2019).

In contrast, organic soil-based cultivation supports microbial diversity and root–soil interactions that influence mineral uptake and fiber development. Studies have demonstrated that organic amendments like vermicompost and green manure promote the availability of micronutrients such as magnesium and zinc, which are essential for enzymatic functions and structural integrity in spinach leaves (Irin & Hasanuzzaman, 2024; Sande et al., 2024). Additionally, the gradual nutrient release from organic sources encourages sustained growth and higher dry matter accumulation, reflected in increased fiber and ash content (Gautam et al., 2025; Mulatu & Bayata, 2024). These findings suggest that while soilless systems may optimize certain nutrients, soil-based organic methods contribute to a broader spectrum of nutritional and ecological benefits (Lori et al., 2017).

3.4.2 Cowpea [*Vigna unguiculata* (L.) Walp.]

Recent agronomic trials have revealed that soilless cultivation using NPK fertilizers significantly boosts the protein and fat content of cowpea seeds. According to Adeyemi et al. (2021), NPK-enriched hydroponic systems provide readily available macronutrients that stimulate amino acid synthesis and lipid accumulation, resulting in superior nutritional density. The controlled environment of soilless systems also minimizes nutrient leaching and competition, allowing cowpea plants to efficiently channel resources into seed development (Lakhiar et al., 2025b).

In contrast to conventional cultivation, cowpea grown under organic soilless conditions tends to accumulate higher levels of dietary fiber and carbohydrates. This nutritional enhancement is largely attributed to the use of organic inputs such as compost tea and vermiliquid, which introduce beneficial microbes and complex organic compounds into the root zone. These inputs not only improve root health but also stimulate carbohydrate metabolism by enhancing microbial activity and nutrient availability. According to Carneiro Da Silva et al., 2019b), cowpea is a strategic legume species whose nutritional profile can be significantly influenced by cultivation practices, with organic systems promoting superior health benefits through increased fibre and carbohydrate content. These treatments promote gradual nutrient release and encourage the synthesis of structural polysaccharides, contributing to increased fiber content. Additionally, the presence of humic substances in organic solutions has been linked to improved photosynthetic efficiency and starch accumulation in legumes (Maffia et al., 2025).

Interestingly, soil-based control treatments without added fertilizers resulted in elevated ash and iron levels in cowpea. This outcome highlights the nuanced role of native soil chemistry in micronutrient dynamics. Soils rich in iron oxides or with favorable pH conditions can enhance iron bioavailability, even in the absence of supplementation (Adebayo & Anjorin, 2018). Moreover, ash content, which reflects total mineral accumulation, may be influenced by the natural mineral composition of the soil and its interaction with cowpea root exudates (Lakhiar et al., 2025b).

Cowpea, as a leguminous crop, is naturally adapted to fix atmospheric nitrogen (N_2) through symbiotic associations with rhizobia, thereby reducing its dependence on external nitrogen input. The data above show that while NPK fertilization (e.g., GM1 + FR2) enhanced crude protein levels, it also altered mineral balances such as ash content, reflecting nutrient antagonism. This illustrates that cowpea's inherent ability to fix nitrogen can meet much of its N requirement, but the addition of synthetic N may disrupt the crop's nutrient equilibrium. Studies confirm that cowpea can derive a significant proportion of its nitrogen from biological fixation, often exceeding 60–80% of total N needs under low-input systems (Abdoul-Karim et al., 2025; Mogale et al., 2023a)

From a sustainability perspective, it is not always necessary to apply high levels of nitrogen fertilizer to cowpea, since excessive N can suppress nodulation and reduce the efficiency of biological nitrogen fixation. Instead, balanced fertilization strategies that supply phosphorus and other limiting nutrients, while relying on cowpea's natural N-fixing capacity, are more sustainable. This approach enhances soil fertility, reduces input costs, and minimizes environmental risks associated with nitrogen leaching and greenhouse gas emissions. Intercropping studies in sub-Saharan Africa have demonstrated that cowpea's N-fixation contributes to the productivity of companion cereals, underscoring its role in sustainable agroecosystems (Mogale et al., 2023b).

Thus, while cowpea can benefit from judicious nutrient supplementation, particularly phosphorus and micronutrients, the routine use of synthetic nitrogen fertilizers is not sustainable for this crop. Leveraging its biological nitrogen fixation capacity is a more ecologically sound strategy that supports both crop productivity and long-term soil health.

3.4.3. Amaranth (*Amaranthus viridis* L.).

A comparative analysis of amaranth grown under soilless and soil-based systems revealed notable differences in nutrient composition, influenced by cultivation method. Dry matter content remained consistent in soilless treatments (~89.9%), while soil-based systems exhibited greater variability (86–91%), likely due to environmental fluctuations and uneven nutrient availability (Osumah et al., 2023). Ash content was significantly higher in soilless-grown amaranth, particularly in control treatments (14.71%), suggesting enhanced mineral accumulation compared to soil-based samples (10–13%) (Adeoluwa & Akinyemi, 2014). Crude fat levels were slightly elevated in soil-based systems (up to 10.2%), though soilless treatments also maintained substantial values (8.04–9.03%), possibly due to differences in organic matter and microbial activity (Mndzebele et al., 2023).

Crude fibre was more pronounced in soilless-grown amaranth, especially in control setups (4.72%), compared to soil-based samples (3.2–4.6%), indicating that nutrient stress in hydroponic systems may stimulate fibre biosynthesis (Osumah et al., 2023). Protein content was notably higher in soilless cultivation (23.42–25.06%) than in soil-based treatments (21–24%), which may be attributed to the immediate availability of nitrogen in hydroponic systems that promotes amino acid synthesis (Mndzebele et al., 2023). Conversely, carbohydrate levels were greater in soil-based amaranth (40–45%) than in soilless samples (37.57–42.53%), likely due to gradual nutrient release and microbial interactions that favor carbohydrate metabolism (Adeoluwa & Akinyemi 2014). Iron content followed a similar trend, with soil-based treatments showing higher concentrations (0.021–0.035 mg/g) compared to soilless systems (0.01–0.03 mg/g), possibly due to the presence of native iron oxides in soil (Osumah et al., 2023).

These findings underscore the influence of cultivation method on the nutritional profile of amaranth. Soilless systems appear to favor protein and fibre accumulation, while soil-based systems enhance carbohydrate and iron content. Such insights are valuable for optimizing production strategies to meet specific nutritional and market demands.

3.4.4. Collard (*Brassica oleracea* L.)

Comparative evaluation of the proximate and mineral composition of collard grown under soilless and soil-based cultivation systems, with emphasis on organic, inorganic (NPK), and control treatments, reveals distinct trends in nutrient accumulation influenced by the growing medium and fertilizer type. The nutrient profile of collard varies depending on the cultivation method, revealing how growing conditions influence nutrient density and dietary value (Canazza et al., 2024b).

Soilless treatments exhibited a narrow and consistent range of dry matter values, averaging approximately 89.9%. In contrast, soil-based treatments demonstrated greater variability (86–91%), suggesting that environmental factors inherent to soil systems may contribute to fluctuations in moisture retention and biomass accumulation (Tuxun et al., 2025). Furthermore, soil systems, influenced by heterogeneity in texture, organic matter, and water-holding capacity, may introduce fluctuations that affect plant water status and dry matter yield (Gruda, 2022a).

Ash content, indicative of total mineral presence, ranged from 12.04% to 14.71% in soilless systems, with the control treatment recording the highest value. Soil-based treatments showed slightly elevated ash levels overall (13–16%), particularly under organic fertilization, implying enhanced mineral uptake from naturally enriched substrates, where microbial decomposition facilitates micronutrient solubilization (Othman et al., 2019).

Crude fat content in soilless-grown collard ranged between 8.04% and 9.03%, marginally higher than soil-based counterparts (7.5–9.0%). Although the ranges overlap, the elevated fat levels in soilless systems may reflect optimized nutrient delivery and reduced competition for resources (Tuxun et al., 2025).

Crude fibre was more pronounced in soil-based treatments, especially under organic fertilization (4.8–5.4%), compared to 3.74–4.72% in soilless systems. This suggests that soil environments may better support structural carbohydrate synthesis, possibly due to microbial interactions and root zone complexity (Othman et al., 2019).

Crude Protein content was notably higher in soil-based collard, ranging from 25% to 28%, with organic treatments leading. Soilless systems yielded slightly lower values (23.42–25.06%), though still substantial. The superior protein levels in soil-grown plants may be attributed to enhanced nitrogen mineralization and microbial activity (Gruda, 2018).

Soilless-grown collard demonstrated significantly higher carbohydrate concentrations (37.57–42.53%) compared to soil-based treatments (30–35%). This inverse relationship with protein suggests a metabolic trade-off, where soilless systems may favor energy storage over amino acid synthesis (Tuxun et al., 2025).

Iron levels were modestly higher in soil-based treatments (0.011–0.020 mg/g), particularly under organic fertilization, while soilless systems ranged from 0.01 to 0.03 mg/g. The mineral-rich nature of soil and its buffering capacity and mineral richness of the soil matrix likely contribute to improved micronutrient availability (Othman et al., 2019).

An inverse relationship was observed between protein and carbohydrate concentrations. Soil-based collard, especially under organic treatment, exhibited higher protein levels (25–28%), while soilless-grown samples demonstrated elevated carbohydrate content (37.57–42.53%). This suggests a metabolic trade-off, where nitrogen-rich environments favor protein synthesis, while controlled nutrient regimes in soilless systems promote energy storage compounds. Such physiological responses are consistent with the nutrient allocation strategies of leafy vegetables under varying nitrogen availability (Tuxun et al., 2025).

The findings have practical implications for crop quality optimization. Soilless systems may be preferable for producing energy-dense leafy greens with elevated carbohydrate and fat content, suitable for dietary formulations requiring lower protein intake. In contrast, soil-based systems, particularly those utilizing organic amendments, are better suited for generating protein-rich and mineral-dense produce, aligning with nutritional goals for iron and fibre intake. While soilless cultivation offers precision and year-round production potential, it requires technical infrastructure and careful nutrient management. Soil-based systems, though more variable, may be more accessible and ecologically integrated, especially in resource-limited settings. Future research should explore hybrid cultivation models that combine the microbial richness of soil with the controlled nutrient delivery of soilless systems to optimize both yield and nutritional quality.

Overall, these findings underscore the influence of cultivation method on the nutritional profile of collard. Soilless systems favor carbohydrate and fat accumulation, while soil-based systems enhance protein, fibre, and iron content. These insights can inform targeted production strategies for nutritional optimization.

Further research should explore the bioavailability of micronutrients, as absorption may differ from raw content (Bechoff & Dhuique-Mayer, 2017). Additionally, understanding consumer taste preferences in relation to nutrient shifts could inform dietary adoption and market strategies (Liem & Russell, 2019). Investigating stress physiology and secondary metabolite production in untreated versus amended systems may also reveal mechanisms behind nutrient enrichment and plant resilience (Isah, 2019).

3.5 Effects of different proportions of soilless growth media on the growth performance of selected leafy vegetables

3.5.1. Spinach number of Leaves

Table 18: ANOVA summary of number of leaves

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Potting media	2	6.50	3.250	1.191	0.319
Potting media: Fertilizer type	2	1.23	0.617	0.226	0.799
Fertilizer	4	13.35	3.337	1.223	0.324
Residuals	27	73.67	2.728		

The overall ANOVA results show that under the experimental settings, the number of leaves in spinach at the sampling stage was not significantly changed by the fertilizer regime, media composition, or any combination of these factors. This suggests that the number of spinach leaves in this trial was essentially unaffected by the charcoal-to-coffee-husk ratio used or by whether the plants were fertilized with organic, NPK, or no fertilizer at the time point of sampling.

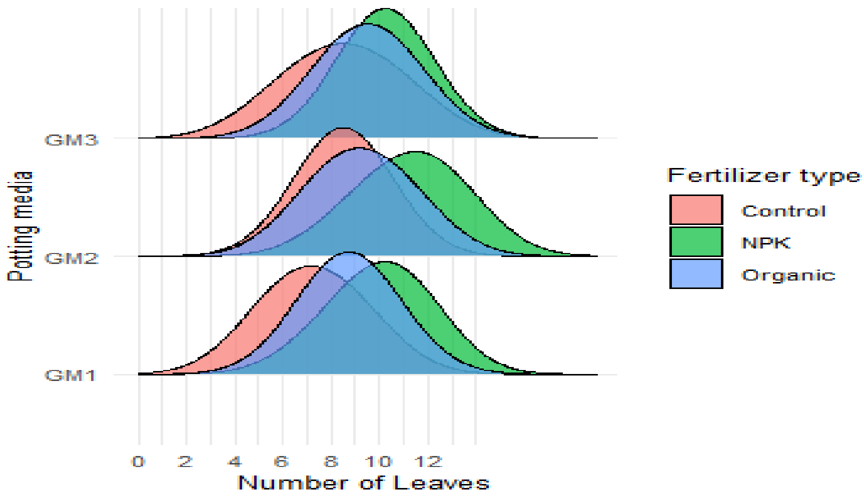


Figure 11: Spinach number of leaves across different growth media

The three-panel ridge plot in Figure 11 displays the distribution of spinach leaf counts under three fertilizer regimes across three soilless media formulations. The overlapping, smooth density graphs show all three curves overlap substantially in every media, reflecting high within-treatment variability and the non-significant ANOVA results for spinach *($p > 0.5$).*

3.5.2. Amaranth number of leaves

Table 19: ANOVA summary of number of leaves

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Potting media	2	81.3	27.086	12.469	2.07e-07 ***
Fertilizer type	2	21.0	10.512	4.839	0.00904 **
Potting media: Fertilizer type	4	15.4	3.856	1.775	0.13608
Residuals	170	369.3	2.172		

According to the study, the proportions of the potting media significantly impacted the number of leaves *($p = 2.07 \times 10^{-7}$)*, and growth varied significantly depending on the ratio of charcoal to coffee husks. Because the leaf counts of organic, NPK, and control treatments were statistically different, fertilizer type also had a significant impact ($p = 0.00904$). But the interaction term ($p = 0.136$) was not significant, indicating that there was no antagonistic or synergistic influence and that the fertilizer effects were constant across all media formulations.

3.5.3. Amaranth shoot height

Table 20: ANOVA summary of shoot height

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Potting media	3	153.2	51.07	15.643	4.97e-09 ***
Fertilizer type	2	66.4	33.14	10.164	6.77e-05 ***
Potting media: Fertilizer type	4	20.4	5.11	1.566	0.186
Residuals	170	554.9	3.26		

The ANOVA results show that the proportions of the potting media had the biggest impact on plant height ($p < 0.001$), with some substrate mixes consistently yielding higher plants. Both NPK and organic fertilizers increased growth in comparison to unfertilized controls, indicating that fertilizer type also had a substantial impact ($p < 0.001$). The fact that the interaction term ($p = 0.186$) was not significant, however, suggests that the fertilizer effect was additive and did not exhibit any synergistic influence across all media types.

3.5.4 Collard number of leaves

Table 21: ANOVA summary of number of leaves

	Df	SumSq	Mean Sq	F value	Pr(>F)
Potting media	2	1.56	0.778	0.750	0.482
Fertilizer type	2	37.72	18.861	18.187	9.94e-06 ***
Potting media: Fertilizer type	4	6.94	1.736	1.674	0.185
Residuals	27	28.00	1.037		

According to the study, the measured collard characteristic at 4 weeks was not significantly impacted by the potting material composition alone (*p* = 0.482). In contrast to unfertilized controls, early collard development was significantly increased by both NPK and organic fertilizers, indicating that fertilizer type had a highly significant effect (*p < 0.00001).* Furthermore, the fertilizer advantages were consistent across all substrates without any synergistic or antagonistic effects, as seen by the lack of a significant interaction between media composition and fertilizer type *(p = 0.185).*

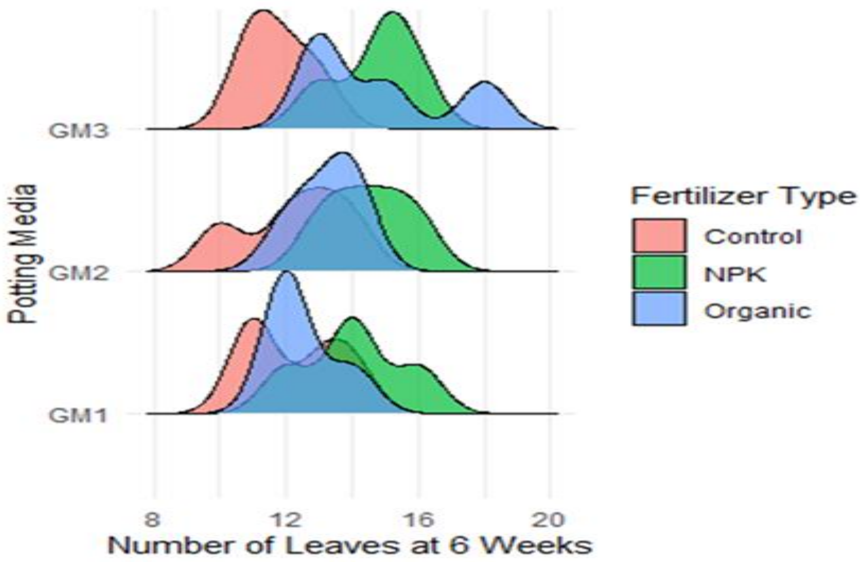


Figure 12: Collard number of leaves across different growth media

The ridge-density panels in figure 12 show the distribution of collard leaf counts for each potting-media formulation under three fertilizer regimes. NPK (green**)** consistently produces the highest leaf counts (peaks around 16–18 leaves), indicating strong promotion of early vegetative production. Organic (blue) is intermediate, with peaks ~14–15 leaves better than unfertilized controls but not as vigorous as NPK. The control (red) shows the lowest leaf numbers (peaks ~10–12 leaves), reflecting the baseline growth without added nutrients. Across all three media, the fertilizer ranking remains the same (NPK > Organic > Control), suggesting potting-media composition had only a minor modulatory effect on leaf number.

3.5.5. Cowpea shoot height

Table 22 ANOVA summary of shoot height

	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Potting media	2	18.2	9.08	2.699	0.0722
Fertilizer type	2	152.0	76.00	22.583	8.32e-09 ***
Potting media: Fertilizer type	4	31.7	7.92	2.352	0.0592
Residuals	99	3.37	3.37		

The ANOVA results show that fertilizer type had a highly significant effect on the shoot height *($p < 0.001$)*, indicating that control, organic, and NPK regimes produced distinctly different outcomes. The potting media, however, showed a marginal trend *($p = 0.072$),* suggesting substrate composition may influence performance but did not reach conventional significance. The potting media and fertilizer type interaction was also marginal *($p = 0.059$)*, hinting at a potential synergistic effect between specific media and fertilizer combinations.

3.6. Discussion

3.6.1. Spinach number of leaves

There was minimal difference in spinach leaf development at this point between media and fertilizer regimes. This implies that spinach, especially leafy cultivars that develop quickly, may sustain consistent early growth under a variety of soilless substrates and nutrient inputs. This is probably because spinach has effective nutrient uptake systems and relatively low biomass requirements in the first few weeks (Zhang et al., 2014). The overlapping distributions indicate consistent leaf counts irrespective of the type of media used, which is beneficial for guaranteeing a steady supply of nutrient-dense, fresh greens. In addition, it shows that, for early-stage spinach leaf production, adjusting the Charcoal: Coffee-husk ratio in the potting mix does not materially alter outcomes.

Because the composition of the substrate had no marked effect on spinach development, growers can utilize locally accessible, renewable potting material, like used coffee husk alone, without compromising output. By doing this, dependency on peat is decreased, and the negative effects of peat extraction on carbon and biodiversity are reduced (Fernández, 2022; Gruda & Fernández, 2022). The non-significant fertilizer effect suggests that NPK can boost early spinach growth even under low-input or organic regimes. This makes it possible to reduce the usage of synthetic fertilizer while preserving performance, reducing greenhouse gas emissions and the risk of eutrophication (Savvas & Gruda, 2018). Although NPK gave the highest mode, the organic treatment still achieved comparable leaf counts in many individual plants. This indicates the potential to replace or reduce synthetic inputs with organic amendments, lowering energy use, greenhouse-gas emissions, and nutrient runoff. Since substrate composition had little effect on leaf count, growers might prioritize locally available, renewable media (e.g., spent coffee husk alone) over imported or carbon-intensive substrates without sacrificing yield.

In this study, the consistent early development across treatments guarantees consistent yields of nutrient-dense spinach leaves that are high in iron, calcium, and vitamins A, C, and K (Jiménez-Aguilar & Grusak, 2015). Furthermore, increasing secondary metabolite levels (polyphenols, antioxidants) with organic fertilization might improve the leaves' functional food value even if biomass is similar (Uusiku et al., 2010b). The results indicate that reliable spinach production under different substrate and fertilizer regimes promotes small-scale, localized soilless production, which is essential for urban and peri-urban food systems dealing with supply-chain interruptions. With minimal fertilizer and a variety of substrate options, growers can achieve consistent yields, lowering expenses and logistical obstacles that frequently restrict access to fresh greens in environments with limited resources (Eigenbrod & Gruda, 2015a).

Spinach growth in soilless culture shows that it is extremely resilient to fertilizer and substrate formulation; these would give producers a great deal of freedom. Through resilient, decentralized production, they can prioritize locally sourced, sustainable media and low-input or organic nutrition without sacrificing yield, supporting environmental sustainability, preserving the nutritional value of this essential leafy vegetable, and enhancing food security.

3.6.2. Amaranth number of leaves

To maximize leaf number in amaranth, selecting the best-performing soilless substrate formulation should be prioritized, with the application of either organic or inorganic fertilizer to boost leaf count. The results show that the effect is additive rather than conditional on media (A. T. Ahmad et al., 2019; Asaduzzaman et al., 2015). Since there is no interaction, optimum use of substrate and fertilizer independently can be utilized, simplifying trial designs and grower decisions (Wiggins et al., 2020a). The use of charcoal and coffee-husk residues as soilless substrates not only diverts these byproducts from waste streams but also reduces reliance on peat and other nonrenewable media, thereby lowering the carbon footprint of production (Rathnayake et al., 2021).

Compared to traditional field systems, soilless agriculture in well-drained, optimized substrates uses up to 90% less water, easing the strain on freshwater resources and lowering nutrient-laden runoff (Elmulthum et al., 2023). In addition, the accurate application of inorganic or organic fertilizers in closed or semi-closed systems reduces phosphate and nitrate leaching into nearby ecosystems, preventing streams from becoming eutrophic (Hina, 2024). The farmers may consistently produce leafy greens with high amounts of vitamins (A, C, K), minerals (iron, calcium), and phytochemicals throughout the seasons by optimizing substrate and fertilizer separately, as the study demonstrates additive rather than interaction effects (Ayamba et al., 2023; Machado et al., 2020; Mampholo et al., 2018).

Although slightly less intensive than NPK for biomass, organic fertilizer regimens frequently increase the amounts of phenolic and antioxidant chemicals in leaves, contributing useful health benefits to yield (Ibrahim et al., 2013; Uusiku et al., 2010c),. Controlled soilless systems decouple leafy-vegetable cultivation from seasonal and climatic constraints, enabling continuous fresh-produce supply in urban and peri-urban areas, thus reducing dependence on long supply chains (Joshi et al., 2022; Kalaivanan et al., 2023a). Adopting a range of leafy vegetables that are cultivated without soil, especially some that are undervalued, can help vulnerable communities consume more micronutrients and protect soil-based systems against crop failures (Issa-Zacharia et al., 2024; Junge & Buchenrieder, 2025).

The selection of potting media significantly influences amaranth leaf growth, whereas fertilizer type has an effect but to a lesser extent. Since their interaction is not statistically significant, one does not strongly depend on the other. The clear, additive benefits of both soilless potting growth media formulation and fertilizer regime demonstrated in this study provide a blueprint for sustainable leafy-vegetable production. Growers can optimize soilless media for physical and ecological advantages, while independently applying the fertilizer regime that best balances yield, nutritional quality, and environmental stewardship.

3.6.3. Amaranth shoot height

The results indicate that, for optimal amaranth shoot height in soilless cultivation, priority should be given to selecting the most suitable potting media formulation. Fertilizer application can then be adjusted independently, as no specific interaction between media and fertilizer is necessary for growth enhancement. Furthermore, this finding shows that in soilless amaranth cultivation, substrate formulation serves as the primary factor influencing shoot height, while the fertilizer regime provides a secondary enhancement. By selecting the most effective potting media and subsequently applying the chosen fertilizer, whether organic or inorganic, consistent early vegetative growth is ensured, streamlining management practices for optimal crop development.

Research indicates that optimizing the growth medium allows for the substitution of organic amendments without compromising yield, thereby supporting circular economy principles. Compostable organics help reduce greenhouse gas emissions and lower embodied energy by partially replacing synthetic inputs (Fan et al., 2023). Additionally, the composting of organics serves as an effective strategy to mitigate environmental impact while maintaining productivity (Fan et al., 2023; Lawrence & Melgar, 2023; Yao et al., 2024). By integrating these practices, Amaranth can be cultivated year-round in controlled soilless systems, enhancing resilience against climate variability and seasonal food shortages (Eigenbrod & Gruda, 2015b).

Amaranth, a nutrient-dense crop rich in protein, vitamins, and minerals, plays a crucial role in addressing micronutrient deficiencies in populations vulnerable to hidden hunger (Aderibigbe et al., 2022). The straightforward additive effects facilitate broader access to fresh greens, allowing urban and small-scale gardeners to implement efficient cultivation methods without requiring extensive agronomic expertise (Dhar et al., 2024). The incorporation of charcoal dust and spent coffee husks in soilless media helps reduce reliance on peat, thereby contributing to the conservation of peatland carbon sinks (Gruda & Fernández, 2022). Additionally, precise fertilizer application, independent of complex media-fertilizer interactions, minimizes nutrient leaching, thereby reducing the risk of eutrophication in surrounding ecosystems (Abdi et al., 2023; Entry & Sojka, 2010; Reisinger et al., 2025);. Furthermore, the findings indicate that specialized media-fertilizer pairings are unnecessary. This suggests that producers can standardize substrate and nutrient management protocols, streamlining supply chains and minimizing resource waste (Cassani & Gomez-Zavaglia, 2022).

This study provides a scalable, resource-efficient blueprint for sustainable amaranth farming by separating fertilizer selection from medium optimization, which is made possible by their additive effects. Utilizing locally available waste materials as growth substrates, applying organic or inorganic fertilizers in accordance with crop requirements, and maintaining consistent harvests of nutrient-rich leafy biomass enables growers to enhance food security while simultaneously advancing principles of environmental sustainability.

3.6.4. Collard number of leaves

At four weeks after planting, collard growth parameters were not significantly influenced by the composition of the potting media alone ($p = 0.482$). This finding aligns with previous studies that emphasize the limited role of substrate type in determining early Brassica growth when nutrient availability is controlled (Sauman Ham et al., 2022; Yang et al., 2024). In hydroponic and soilless systems, media primarily serve as a physical support, with nutrient supply being the dominant factor influencing growth outcomes. Thus, the absence of a significant media effect underscores the importance of fertilizer regimes over substrate composition in early collard development.

In contrast, fertilizer type exerted a highly significant effect on collard growth ($p < 0.00001$), with both NPK and organic fertilizers outperforming unfertilized controls. This result is consistent with findings that collards, like other leafy Brassicas, are medium to heavy feeders requiring substantial nitrogen inputs to support rapid leaf expansion and chlorophyll synthesis (Helalya et al., 2020; Inzule, 2011). The observed growth enhancement under both mineral and organic regimes suggests that collards can effectively utilize diverse nutrient sources, provided they are supplied in adequate amounts. These results reinforce the agronomic recommendation that precise nutrient management, rather than substrate manipulation, is the key driver of early collard vigor.

Finally, the lack of a significant interaction between media composition and fertilizer type *($p = 0.185$)* indicates that fertilizer benefits were consistent across all tested substrates, without synergistic or antagonistic effects. This finding supports broader evidence that nutrient availability exerts a uniform influence across different media types, provided water and aeration are adequate (Yang et al., 2024; Hamdani et al., 2022). From a sustainability perspective, this suggests that growers can prioritize fertilizer management strategies without concern for complex media fertilizer interactions. Controlled soilless systems with carefully planned fertilizer cycles therefore represent a viable pathway to optimize collard production while minimizing nutrient losses and environmental risks.

Both NPK and organic fertilizers significantly increased the number of leaves in collard compared to unfertilized controls. According to research, in soilless systems, optimizing biomass accumulation still depends on precise nutrient input (Pokhare, 2023). The non-significant potting-media effect suggests that altering the charcoal: coffee-husk ratio (e.g., GM1, GM2, and GM3) does not materially influence collard leaf development at 4 weeks, once sufficient nutrients are available. The interaction term is non-significant *($p = 0.185$),* implying that fertilizer benefits are consistent across all media types; there is no special best pairing. Growers can optimize fertilizer independently of substrate choice. By prioritizing fertilizer management over specialized substrates, peat usage can be decreased. The utilization of local residues such as coffee husks and charcoal dust, rather than relying on yield-disadvantaging substrates, contributes to peatland conservation and advances the principles of a circular economy (Jindo et al., 2020).

Research has shown that in urban and resource-constrained settings, reliable early growth under organic fertilizer comparable to NPK offers an effective approach for producing micronutrient-rich collard greens while minimizing synthetic inputs, ensuring consistent year-round availability (Kebrom et al., 2019). In soilless cultivation, nutrient availability is the key factor influencing early Collard development, while substrate composition has minimal impact. Due to the absence of interaction effects, variations in the charcoal-to-coffee-husk ratio do not influence the fertilizer response (Altland & Locke, 2012; Chrysargyris et al., 2020). Given the limited early impact of media composition, farmers can simplify substrate selection by opting for readily available, low-impact materials such as used coffee husks rather than carbon-intensive alternatives like peat (Gruda, 2022). Prioritizing precise fertilizer management helps mitigate downstream eutrophication risks and prevents excessive application by ensuring controlled nutrient delivery. Strong fertilizer effects support consistent early leaf expansion, facilitating the production of nutrient-rich Collard greens, which are abundant in minerals and vitamins A, C, and K. Since organic fertilizers perform comparably to synthetic fertilizers in this context, producers can enhance phytonutrient profiles without compromising early growth (Awal et al., 2021). Without the need for specific substrate-fertilizer pairings, growers can focus on optimizing organic or NPK-based fertilizer regimes, reducing costs and technical barriers, particularly in urban and resource-constrained settings. Enhanced early growth accelerates crop cycles and enables more frequent harvests, increasing the year-round availability of fresh vegetables in local food systems (Kalaivanan et al., 2023b).

The findings clearly indicate that the primary factor influencing early collard growth is the fertilizer regime, particularly the application of NPK. This suggests that growers should focus on precisely supplying the crop with essential nutrients while minimizing excess inputs that could otherwise leach into groundwater or run off into surface waters. Rather than applying fertilizers directly into the soil in a single dose, controlled soilless systems with carefully planned fertilizer cycles provide a more sustainable alternative, thereby reducing the risk of eutrophication (Shingo & Ventura, 2009; Tei et al., 2020). Despite the highest reaction from NPK, organic fertilizers nevertheless resulted in significant growth. This therefore suggests that reliance on synthetic inputs and their associated carbon footprint can be decreased by including well-stabilized organic amendments, which can recycle agricultural leftovers (manure, compost), and create soil-like microbial communities in the substrate (Fan et al., 2023). According to studies, the charcoal to coffee-husk media compositions transform two waste streams into useful potting substrates by valuing charcoal dust and leftover coffee husk. While media composition was less important for early growth, these materials can help achieve the circular economy goals of improving aeration, water-holding capacity, and carbon sequestration (Tamilselvan et al., 2024). By substituting locally produced, renewable wastes for peat, producers minimize the greenhouse-gas emissions linked to peat extraction and contribute to the preservation of peatland ecosystems, which are important carbon sinks (Hashemi et al., 2024). Research has also shown that in urban agriculture or water-scarce areas, hydroponic and substrate-based soilless horticulture can reduce water consumption by up to 90% when compared to field production (Ghimire et al., 2023).

Stabilizing food access in urban or resource-limited locations requires a more regular supply, shorter supply chains, and lower post-harvest losses, which are made possible by controlled settings that decouple the growing of green vegetables from seasonal and geographic constraints (Mead et al., 2024). Therefore, in order to fulfill the growing demand for fresh greens in both developed and developing locations, rapid, dependable early growth under optimum fertilizer regimes allows faster crop turns and improved overall production per unit area (Byiringiro, 2023). In addition, by lowering the possibility of contamination from heavy metals or soil pathogens, soilless systems enhance food safety and customer trust in the quality of leafy vegetables (Chen et al., 2024).

In summary, soilless cultivation systems that emphasize precise fertilizer management within renewable, waste-derived substrates offer a pathway to more resource-efficient and environmentally sustainable leafy vegetable production. This approach not only enhances food security by stabilizing yields, improving crop quality, and enabling year-round local cultivation but also advances environmental sustainability through water conservation, waste repurposing, and reduced fertilizer pollution.

3.6.5. Cowpea shoots height

The extremely strong effect of fertilizer type *($p < 0.001$)* indicates that providing an adequate nutrient solution is the primary driver of cowpea performance in soilless culture. This supports the theory that optimized nutrient formulations in hydroponic cowpea significantly boost biomass and nutrient uptake compared to unfertilized controls. This clearly shows that precise control of macro- and micronutrient concentrations inorganic (NPK) or well-balanced organic formulations ensures plants meet their physiological demands, leading to more robust shoot and root development (Ahmed et al., 2024).

While there was a trend toward potting-media composition (charcoal: coffee-husk ratios) influencing cowpea development ($p \approx 0.07$), it fell short of conventional significance. This implies that after ideal nutrition is provided, root-zone physical characteristics in a recirculating nutrient solution system take a backseat. As long as proper oxygenation and water retention are maintained, similar assessments point out that substrate impacts on hydroponic legumes are frequently negligible in comparison to the dominant influence of nutrient solution chemistry (Sambo et al., 2019).

In addition, the marginal interaction ($p \approx 0.059$) suggests that some combinations of substrate and fertilizer may offer minor benefits; for example, a medium that buffers pH better may improve the availability of nutrients from organic amendments (Naik et al., 2016). Other soilless systems have demonstrated synergistic yield and quality benefits when plant-growth-promoting rhizobacteria (PGPR) are incorporated into organic fertilizer regimes, indicating a way to enhance these marginal interaction effects (Ikiz et al., 2024).

Therefore, to optimize cowpea growth in soilless systems, careful consideration should be given to select the appropriate fertilizer regime, particularly NPK or a well-formulated organic blend. Adjustments to the media can improve outcomes (Bondok et al., 2024b). By considering the potent fertilizer effect, switching from synthetic to premium organic fertilizers might significantly lower the carbon footprint and leaching risk of the system while just slightly reducing production (Mdlambuzi et al., 2021).

It can therefore be suggested that targeted trials concentrating on the most promising combination are necessary, as the marginal interaction indicates that adjusting substrate composition in combination with fertilizer selection could unleash additional improvements (Montgomery & Srinivasan, 2019; Wiggins et al., 2020b).

In soilless cowpea culture, nutrient regime is the critical lever for enhancing vegetative performance, whereas potting growth media plays a secondary, supportive role. There is some indication of a beneficial interaction between certain media and fertilizer combinations, but confirming and harnessing that synergy will require additional focused experimentation.

3.7. Thesis Conclusion

This study on the nutritive profiles of leafy vegetables grown on enriched soilless growth media confirms that soilless cultivation systems, particularly those utilizing waste-derived substrates such as charcoal dust and coffee husks, provide a sustainable and nutritionally advantageous alternative to conventional soil-based agriculture. Fertilizer regimes significantly shaped nutrient composition: inorganic inputs enhanced crude protein and fibre, while organic amendments promoted carbohydrate and iron accumulation. Across all measured parameters dry matter, ash, fat, fibre, protein, carbohydrate, and iron soilless systems consistently produced higher values, thereby validating the central focus of the thesis on nutritive enhancement through enriched growth media.

It is important, however, to interpret the comparative advantage of soilless systems with caution. The observed superiority may partly reflect differences in soil fertility, nutrient availability, and water dynamics, as well as the cultivation environment. Soilless substrates often provide more consistent nutrient release and moisture regulation, while greenhouse or controlled conditions reduce environmental stress compared to open-field soil cultivation. Thus, the enhanced nutritive profiles observed in soilless systems result not only from substrate enrichment but also from contextual factors that may favour nutrient uptake and accumulation

Crop-specific responses revealed that spinach and cowpea exhibited high resilience and nutrient responsiveness. In cowpea, resilience was indicated by its stable dry matter accumulation, consistently elevated crude protein levels, and capacity to maintain nutritional quality across diverse treatments, reflecting its physiological adaptability as a legume capable of biological nitrogen fixation. In contrast, amaranth and collard benefited more from tailored media compositions, underscoring the importance of substrate optimization for non-leguminous crops. These findings emphasize the value of strategic nutrient and substrate management in maximizing both yield and dietary quality, particularly in resource-constrained and urban environments.

Taken together, the comparative analysis affirms that enriched soilless growth media can transform leafy vegetable production by simultaneously addressing challenges of soil fertility decline, nutrient variability, and urban land scarcity. By integrating waste-derived substrates with strategic fertilizer regimes, soilless agriculture emerges as a viable pathway for enhancing nutritive profiles, strengthening food security, and promoting sustainable dietary improvement. Cowpea's demonstrated resilience further highlights the potential of legumes to anchor sustainable cropping systems, ensuring both yield stability and nutritional quality in resource-limited settings**.**

3.8 Future Research

Building on the findings of this study, future research should explore the long-term sustainability of enriched soilless growth media, particularly in relation to nutrient cycling, substrate reuse, and environmental impacts. While waste-derived substrates such as charcoal dust and coffee husks demonstrated clear nutritional advantages, further work is needed to assess their durability, microbial dynamics, and potential for continuous cultivation cycles. Such studies would provide critical insights into the scalability of soilless systems in both rural and urban contexts.

Future recommendations to address the limitation of nutrient variability in organic fertilizers include developing standardized nutrient profiling methods, promoting integrated use with inorganic fertilizers, and advancing processing techniques to stabilize nutrient content. Additionally, investment in affordable nutrient testing tools and farmer training programs would help ensure more precise and efficient nutrient management.

Furthermore, although the present study has demonstrated clear nutritive advantages of soilless substrates formulated from charcoal dust and coffee husks, it is important to recognize that future investigations should incorporate systematic characterization of particle size distribution. The physical architecture of substrate particles directly governs water retention, aeration, and nutrient dynamics, and thus quantifying particle size fractions would enhance reproducibility and strengthen the translation of these findings into practical cultivation systems.

Additionally, targeted biofortification strategies should be investigated to enhance micronutrient density, especially iron and zinc, which remain limiting in cowpea and other leafy vegetables under fertilized conditions. Integrating genetic approaches with agronomic management could yield crops that balance high productivity with improved dietary quality. Research on intercropping systems involving legumes like cowpea could also clarify how biological nitrogen fixation contributes to nutrient enrichment in companion crops, thereby reducing reliance on synthetic fertilizers.

Finally, future studies should evaluate the socio-economic feasibility of adopting enriched soilless systems in resource-limited settings. This includes cost-benefit analyses, farmer adoption studies, and assessments of urban agriculture models that leverage limited space for high-nutrient food production. By linking agronomic performance with nutritional outcomes and socio-economic viability, future research can position enriched soilless growth media as a transformative solution for food security, dietary improvement, and sustainable agriculture in the face of global resource constraints.

Acknowledgements

This study was supported by:

- The PhD School in Agro-Food System (Agrisystem) of the Università Cattolica del Sacro Cuore, Piacenza (Italy)
- Bukalasa Agricultural College (Uganda)

Competing interests

The authors have declared that no competing interests exist.

References

Abawari, R. A. (2022). Organic and bio-fertilizer inputs in coffee production system, coffee cultivation constraints and the role of coffee in coffee cultivation sectors: A review.

Abdi, D. E., Blanchard, J., Fields, J. S., Santos, L., Beasley, L., & Beasley, J. (2023). Reducing Anion Nutrient Leaching Losses from a Short-Cycle Container-Grown Crop (Tagetes patula) Using Activated Aluminum. Agriculture, 13(5), 1028. https://doi.org/10.3390/agriculture13051028

Abdoul-Karim, T. D., Abdel-Kader, A. S., Soulé, M., Sareye, A., Sanoussi, A., & Yacoubou, B. (2025). Short-term effects of cowpea (Vigna Unguiculata [L.] Walp) cultivation and mineral fertilization on soil bacterial abundance and chemical properties. Environmental Challenges, 20, 101292. https://doi.org/10.1016/j.envc.2025.101292

Adebayo,R.A. & Anjorin,O.O. (2018). Assessment of entomocidal effects of solar radiation for the management of cowpea seed beetle Callosobruchus maculatus). 18(1), 21–26.

Adekayode, F., & Ogunkoya, M. (2011). Comparative effects of organic compost and NPK fertilizer on soil fertility, yield and quality of amaranth in southwest Nigeria. International Journal of Biological and Chemical Sciences, 5(2). https://doi.org/10.4314/ijbcs.v5i2.72087

Adekiya, A. O., Ejue, W. S., Olayanju, A., Dunsin, O., Aboyeji, C. M., Aremu, C., Adegbite, K., & Akinpelu, O. (2020). Different organic manure sources and NPK fertilizer on soil chemical properties, growth, yield and quality of okra. Scientific Reports, 10(1), 16083. https://doi.org/10.1038/s41598-020-73291-x

Adeoluwa,O.O. & Akinyemi,O.S. (2014). Amaranths (Amaranthus viridis) dry matter and soil qualities: Organic vs inorganic fertilizers.

Aderibigbe, O. R., Ezekiel, O. O., Owolade, S. O., Korese, J. K., Sturm, B., & Hensel, O. (2022). Exploring the potentials of underutilized grain amaranth (Amaranthus spp.) along the value chain for food and nutrition security: A review. Critical Reviews in Food Science and Nutrition, 62(3), 656–669. https://doi.org/10.1080/10408398.2020.1825323

Adeyemi, T. A., Adeoye, S. A., Ogunyemi, T. J., Adedeji, E. A., Oluyemi, B., & Ojo, V. O. A. (2021). Comparisons of nutrient solutions from organic and chemical fertilizer sources on herbage yield and quality of hydroponically produced maize fodder. Journal of Plant Nutrition, 44(9), 1258–1267. https://doi.org/10.1080/01904167.2020.1845382

Adhikary, D., Khatri-Chhetri, U., & Slaski, J. (2020). Amaranth: An Ancient and High-Quality Wholesome Crop. In V. Y. Waisundara (Ed.), Nutritional Value of Amaranth. IntechOpen. https://doi.org/10.5772/intechopen.88093

Affrifah, N. S., Phillips, R. D., & Saalia, F. K. (2022a). Cowpeas: Nutritional profile, processing methods and products—A review. Legume Science, 4(3), e131. https://doi.org/10.1002/leg3.131

AGRA. (2018). Africa Agriculture Status Report 2018: Catalyzing government capacity to drive agricultural transformation. Alliance for a Green Revolution in Africa.

Ahmad, A., Khan, A., Ullah, F., Hassan, M. A., Iqbal, J., Jun, W., He, S., & Zhaorong, D. (2025). Integration of organic–inorganic nitrogen fertilization on nitrogen conversion in soil. Frontiers in Plant Science, 16, 1688878. https://doi.org/10.3389/fpls.2025.1688878

Ahmad, A. T., Bello, I. U., Jibril, S. M., Kolawole, O. S., Ogah, J. J., & Daniel, S. (2019). Comparative evaluation of the effects of organic and inorganic fertilizers on the vegetative growth of spleen amaranth (Amaranthus dubius L). Journal of Applied Sciences and Environmental Management, 23(2), 359. https://doi.org/10.4314/jasem.v23i2.24

Ahmed, N., Zhang, B., Chachar, Z., Li, J., Xiao, G., Wang, Q., Hayat, F., Deng, L., Narejo, M.-N., Bozdar, B., & Tu, P. (2024). Micronutrients and their effects on Horticultural crop quality, productivity and sustainability. Scientia Horticulturae, 323, 112512. https://doi.org/10.1016/j.scienta.2023.112512

Alimi, T., Ajewole, O. C., Olubode-Awosolo, O. O., & Idowu, E. O. (2007). Organic and inorganic fertilizer for vegetable production under tropical conditions. 1, 120–136.

Altland, J. E., & Locke, J. C. (2012). Biochar Affects Macronutrient Leaching from a Soilless Substrate. HortScience, 47(8), 1136–1140. https://doi.org/10.21273/HORTSCI.47.8.1136

Amos,A.D., Adamu,H.L., Abel,M., Usman,A.G., & Abinya,R. (2023). Comparative study on the nutritional composition of African spinach produced using organic and inorganic fertilizer. 8(1), 33–36.

Asaduzzaman, Md., Saifullah, Md., Mollick, A. K. M. S. R., Hossain, Md. M., Halim, G. M. A., & Asao, T. (2015). Influence of Soilless Culture Substrate on Improvement of Yield and Produce Quality of Horticultural Crops. In Md. Asaduzzaman (Ed.), Soilless Culture—Use of Substrates for the Production of Quality Horticultural Crops. InTech. https://doi.org/10.5772/59708

Aslam, T., Maqsood, M., Jamshaid, I., Ashraf, K., Zaidi, F., Khalid, S., Shah, F. ul H., Noreen, S., & Maria. (2020). Health Benefits and Therapeutic importance of green leafy vegetables (GLVs). European Academic Research, 8, 4213–4229.

Association of Official Analytical Chemists. (2000). Official Methods of Analysis. AOAC International.

Awal, R., Hassan, A. E., Abbas, F., Fares, A., Bayabil, H. K., Ray, R. L., & Woldesenbet, S. (2021). Patterns of Nutrient Dynamics within and below the Rootzone of Collard Greens Grown under Different Organic Amendment Types and Rates. Sustainability, 13(12), 6857. https://doi.org/10.3390/su13126857

Ayamba, B. E., Abaidoo, R. C., Opoku, A., & Ewusi-Mensah, N. (2023). Mechanisms for nutrient interactions from organic amendments and mineral fertilizer inputs under cropping systems: A review. PeerJ, 11, e15135. https://doi.org/10.7717/peerj.15135

Ayenew, H. Y., Biadgilign, S., Schickramm, L., Abate Kassa, G., & Sauer, J. (2018). Production diversification, dietary diversity and consumption seasonality: Panel data evidence from Nigeria. 18(1), 988.

Ayodele, V. I., Nkabinde, R. M., & Ngobeni, T. V. (2010). PRODUCTION AND QUALITY OF AMARANTHUS SPECIES UNDER DIFFERENT FERTILIZER TREATMENTS. Acta Horticulturae, (852), 253–260. https://doi.org/10.17660/ActaHortic.2010.852.31

Balasubramaniam, A. K., Saste, G., Kureshi, A. A., Mulay, V., & Hingorani, L. (2025). Nutritional and health beneficial properties of spinach (Spinacia oleracea L): A comprehensive review. Pharmacological Research - Natural Products, 8, 100368. https://doi.org/10.1016/j.prenap.2025.100368

Bandera, A. D., & Magolama, A. A. (2023). Application of different fertilizer types and levels on vegetable production: A critical review.

Baraniak, J., & Kania-Dobrowolska, M. (2022). The Dual Nature of Amaranth—Functional Food and Potential Medicine. Foods, 11(4), 618. https://doi.org/10.3390/foods11040618

Batabyal, K. (2017). Nutrient Management for Improving Crop, Soil, and Environmental Quality. In M. Naeem, A. A. Ansari, & S. S. Gill (Eds.), Essential Plant Nutrients (pp. 445–464). Springer International Publishing. https://doi.org/10.1007/978-3-319-58841-4_18

Bechoff, A., & Dhuique-Mayer, C. (2017). Factors influencing micronutrient bioavailability in biofortified crops. Annals of the New York Academy of Sciences, 1390(1), 74–87. https://doi.org/10.1111/nyas.13301

Bisht, N., & Singh Chauhan, P. (2021). Excessive and Disproportionate Use of Chemicals Cause Soil Contamination and Nutritional Stress. In M. L. Larramendy & S. Soloneski (Eds.), Soil Contamination—Threats and Sustainable Solutions. IntechOpen. https://doi.org/10.5772/intechopen.94593

Bondok, A. A. T., Saker, H. M., Abo-Marzoka, S. A., Saad-Allah, K. M., & Rady, A. M. S. (2024a). Cowpea (Vigna unguiculata L. Walp) morpho-physiological and yield responses to chemical, organic, and biofertilizers at various watering levels utilizing drip irrigation system. Plant Production Science, 27(2), 110–124. https://doi.org/10.1080/1343943X.2024.2340833

Bondok, A. A. T., Saker, H. M., Abo-Marzoka, S. A., Saad-Allah, K. M., & Rady, A. M. S. (2024b). Cowpea (Vigna unguiculata L. Walp) morpho-physiological and yield responses to chemical, organic, and biofertilizers at various watering levels utilizing drip irrigation system. Plant Production Science, 27(2), 110–124. https://doi.org/10.1080/1343943X.2024.2340833

Botanical online. (2024). Amaranth composition. https://www.botanical-online.com/en/food/amaranth-composition

Bowen University, Ogundare, D., & Tanimola, A. (2022). Nutritional composition of some selected, unprocessed amaranth grain (Amaranthus spp) varieties in Nigeria. African Journal of Food, Agriculture, Nutrition and Development, 22(113), 21383–21396. https://doi.org/10.18697/ajfand.113.19835

Breve, M. N., Josiane, E. Y., & Tsieri, M. D. M. (2023). Nutritional Study of Four Leafy Vegetables Produced and Sold in the Southern Zone of Brazzaville (Republic of Congo). Asian Food Science Journal, 22(8), 28–40. https://doi.org/10.9734/afsj/2023/v22i8651

Breza, L. C., & Grandy, A. S. (2025). Organic amendments tighten nitrogen cycling in agricultural soils: A meta-analysis on gross nitrogen flux. Frontiers in Agronomy, 7, 1472749. https://doi.org/10.3389/fagro.2025.1472749

Britz, E., Cyster, L., Samuels, I., Cupido, C., Masemola, L., Ngcobo, N., Manganyi, F., & Müller, F. (2023). Nitrogen fertilization increases the growth and nutritional quality of the forage legume, Calobota sericea – A preliminary investigation. Heliyon, 9(2), e13535. https://doi.org/10.1016/j.heliyon.2023.e13535

Byiringiro, E. (2023). Effect of Different Fertilizer Rates and Irrigation Depth on Growth and Yield of Two Lettuce Varieties in Outdoor Hydroponic Farming. SSRN. https://doi.org/10.2139/ssrn.4646381

Canazza, E., Tessari, P., Mayr Marangon, C., & Lante, A. (2024a). Nutritional Profile and Chlorophyll Intake of Collard Green as a Convenience Food. Nutrients, 16(23), 4015. https://doi.org/10.3390/nu16234015

Canazza, E., Tessari, P., Mayr Marangon, C., & Lante, A. (2024b). Nutritional Profile and Chlorophyll Intake of Collard Green as a Convenience Food. Nutrients, 16(23), 4015. https://doi.org/10.3390/nu16234015

Carneiro Da Silva, A., Da Costa Santos, D., Lopes Teixeira Junior, D., Bento Da Silva, P., Cavalcante Dos Santos, R., & Siviero, A. (2019a). Cowpea: A Strategic Legume Species for Food Security and Health. In J. C. Jimenez-Lopez & A. Clemente (Eds.), Legume Seed Nutraceutical Research. IntechOpen. https://doi.org/10.5772/intechopen.79006

Carneiro Da Silva, A., Da Costa Santos, D., Lopes Teixeira Junior, D., Bento Da Silva, P., Cavalcante Dos Santos, R., & Siviero, A. (2019b). Cowpea: A Strategic Legume Species for Food Security and Health. In J. C. Jimenez-Lopez & A. Clemente (Eds.), Legume Seed Nutraceutical Research. IntechOpen. https://doi.org/10.5772/intechopen.79006

Carneiro Da Silva, A., De Freitas Barbosa, M., Bento Da Silva, P., Peres De Oliveira, J., Loureiro Da Silva, T., Lopes Teixeira Junior, D., & De Moura Rocha, M. (2021). Health Benefits and Industrial Applications of Functional Cowpea Seed Proteins. In J. Carlos Jimenez-Lopez (Ed.), Grain and Seed Proteins Functionality. IntechOpen. https://doi.org/10.5772/intechopen.96257

Carvalho, M., Carnide, V., Sobreira, C., Castro, I., Coutinho, J., Barros, A.I., & Rosa, E.A. (2022). Cowpea Immature Pods and Grains Evaluation: An Opportunity for Different Food Sources.

Cassani, L., & Gomez-Zavaglia, A. (2022). Sustainable Food Systems in Fruits and Vegetables Food Supply Chains. Frontiers in Nutrition, 9, 829061. https://doi.org/10.3389/fnut.2022.829061

Celli, G. B., & Brooks, M. S.-L. (2017). Impact of extraction and processing conditions on betalains and comparison of properties with anthocyanins—A current review. Food Research International (Ottawa, Ont.), 100(Pt 3), 501–509. https://doi.org/10.1016/j.foodres.2016.08.034

Chemutai, R., Mwine,J, Awichi, R., & Bwogi, G. (2019). Effects of NPK and plant tea manure (Tithonia diversifolia) on growth rate of amaranth (Amaranthus cruentus L.) in soilless growing media. 14(2), 1169–1179. https://doi.org/10.5897/AJAR2019.13928

Chen, S., Yao, C., Zhou, J., Ma, H., Jin, J., Song, W., & Kai, Z. (2024). Occurrence and Risk Assessment of Pesticides, Phthalates, and Heavy Metal Residues in Vegetables from Hydroponic and Conventional Cultivation. Foods, 13(8), 1151. https://doi.org/10.3390/foods13081151

Chen, Y., Hu, S., Guo, Z., Cui, T., Zhang, L., Lu, C., Yu, Y., Luo, Z., Fu, H., & Jin, Y. (2021). Effect of balanced nutrient fertilizer: A case study in Pinggu District, Beijing, China. Science of The Total Environment, 754, 142069. https://doi.org/10.1016/j.scitotenv.2020.142069

Chrysargyris, A., Antoniou, O., Xylia, P., Petropoulos, S., & Tzortzakis, N. (2021). The use of spent coffee grounds in growing media for the production of Brassica seedlings in nurseries. Environmental Science and Pollution Research, 28(19), 24279–24290. https://doi.org/10.1007/s11356-020-07944-9

Chrysargyris, A., Prasad, M., Kavanagh, A., & Tzortzakis, N. (2020). Biochar Type, Ratio, and Nutrient Levels in Growing Media Affects Seedling Production and Plant Performance. Agronomy, 10(9), 1421. https://doi.org/10.3390/agronomy10091421

Cobos, Á., & Díaz, O. (2023). 'Superfoods': Reliability of the Information for Consumers Available on the Web. Foods, 12(3), 546. https://doi.org/10.3390/foods12030546

D'Amico, S., & Schoenlechner, R. (2017). Amaranth: Its Unique Nutritional and Health-Promoting Attributes. In Gluten-Free Ancient Grains (pp. 131–159). Elsevier. https://doi.org/10.1016/B978-0-08-100866-9.00006-6

Datta, S.C. (2020). Cowpea as Biomedicine against Covid-19: Enriching Science and Technology Communication Diagnosis and Therapies.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2023). Sector Brief Uganda: Organic Agriculture (p. 8). GIZ. https://www.giz.de/en/downloads/Sector-Brief-Uganda-Organic-Agriculture.pdf

Dhar, S., Boruah, P., Sarma, S., & Gogoi, S. (2024). Urban Agriculture and Community Gardens (pp. 252–266).

Diao, X., Ellis, M., Pauw, K., & Thurlow, J. (2023). Uganda's agrifood system: Structure and drivers of transformation.

Dion, P.-P., Jeanne, T., Thériault, M., Hogue, R., Pepin, S., & Dorais, M. (2020). Nitrogen release from five organic fertilizers commonly used in greenhouse organic horticulture with contrasting effects on bacterial communities. Canadian Journal of Soil Science, 1–16. https://doi.org/10.1139/cjss-2019-0056

Echer, F. R., Cordeiro ,Carlos Felipe dos Santos, & and de la Torre, E. de J. R. (2020). The effects of nitrogen, phosphorus, and potassium levels on the yield and fiber quality of cotton cultivars. Journal of Plant Nutrition, 43(7), 921–932. https://doi.org/10.1080/01904167.2019.1702204

Eigenbrod, C., & Gruda, N. (2015a). Urban vegetable for food security in cities. A review. Agronomy for Sustainable Development, 35(2), 483–498. https://doi.org/10.1007/s13593-014-0273-y

Eigenbrod, C., & Gruda, N. (2015b). Urban vegetable for food security in cities. A review. Agronomy for Sustainable Development, 35(2), 483–498. https://doi.org/10.1007/s13593-014-0273-y

Elmulthum, N. A., Zeineldin, F. I., Al-Khateeb, S. A., Al-Barrak, K. M., Mohammed, T. A., Sattar, M. N., & Mohmand, A. S. (2023). Water Use Efficiency and Economic Evaluation of the Hydroponic versus Conventional Cultivation Systems for Green Fodder Production in Saudi Arabia. Sustainability, 15(1), 822. https://doi.org/10.3390/su15010822

Entry, J. A., & Sojka, R. E. (2010). Matrix-Based Fertilizers Reduce Nutrient Leaching While Maintaining Kentucky Bluegrass Growth. Water, Air, and Soil Pollution, 207(1–4), 181–193. https://doi.org/10.1007/s11270-009-0127-4

Environmental Defenders. (2021). Smallholder farmers in Uganda: Challenges and opportunities.

Fan, X., Chen, X., Chen, T., Liu, X., Song, Y., Tan, S., Chen, Y., Yan, P., & Wang, X. (2023). Effects of substituting synthetic nitrogen with organic amendments on crop yield, net greenhouse gas emissions and carbon footprint: A global meta-analysis. Field Crops Research, 301, 109035. https://doi.org/10.1016/j.fcr.2023.109035

FAO. (2021a). The role of biochar and charcoal residues in soil fertility. https://openknowledge.fao.org/

FAO. (2021b). The state of food security and nutrition in the world 2021. Food and Agriculture Organization of the United Nations.

FAO. (2024). Policymaking for agrifood systems transformation in Uganda.Food and Agriculture Organization of the United Nations.

Farhan, M., Sathish, M., Kiran, R., Mushtaq, A., Baazeem, A., Hasnain, A., Hakim, F., Naqvi, S. A. H., Mubeen, M., Iftikhar, Y., Abbas, A., Hassan, M. Z., & Moustafa, M. (2024). Plant Nitrogen Metabolism: Balancing Resilience to Nutritional Stress and Abiotic Challenges. Phyton, 93(3), 581–609. https://doi.org/10.32604/phyton.2024.046857

Feng, W., Xue, W., Zhao, Z., Shi, Z., Wang, W., Bai, Y., Wang, H., Qiu, P., Xue, J., & Chen, B. (2024a). Nitrogen fertilizer application rate affects the dynamic metabolism of nitrogen and carbohydrates in kernels of waxy maize. Frontiers in Plant Science, 15, 1416397. https://doi.org/10.3389/fpls.2024.1416397

Feng, W., Xue, W., Zhao, Z., Shi, Z., Wang, W., Bai, Y., Wang, H., Qiu, P., Xue, J., & Chen, B. (2024b). Nitrogen fertilizer application rate affects the dynamic metabolism of nitrogen and carbohydrates in kernels of waxy maize. Frontiers in Plant Science, 15, 1416397. https://doi.org/10.3389/fpls.2024.1416397

Fernández, J. A. (2022). Optimizing Soilless Culture Systems and Alternative Growing Media to Current Used Materials. Horticulturae, 8(4), 292. https://doi.org/10.3390/horticulturae8040292

Feyisa, A. S. (2022). Review of the Role of Orphan Crops in Food Security. Research on World Agricultural Economy, 3(2), 1–14. https://doi.org/10.36956/rwae.v3i2.501

FiBL and IFOAM. (2025). The World of Organic Agriculture: Statistics and Emerging Trends 2025. https://www.ifoam.bio/news/global-organic-area-continues-grow-2025

Fidler, M., & Gómez, C. (2025). Evaluating the Effect of Fertilization and Substrate Volumetric Water Content on Compact Tomato and Pepper Plants. HortTechnology, 35(1), 39–51. https://doi.org/10.21273/HORTTECH05529-24

Food Plant Solutions. (2021). Potentially important leafy greens and vegetables of Uganda. Food Plant Solutions Rotary Action Group.

Food Systems Profile—Uganda. (2023). FAO; European Union ; CIRAD; https://doi.org/10.4060/cc4051en

Fuentes-Peñailillo, F., Gutter, K., Vega, R., & Silva, G. C. (2024a). New Generation Sustainable Technologies for Soilless Vegetable Production. Horticulturae, 10(1), 49. https://doi.org/10.3390/horticulturae10010049

Fuentes-Peñailillo, F., Gutter, K., Vega, R., & Silva, G. C. (2024b). New Generation Sustainable Technologies for Soilless Vegetable Production. Horticulturae, 10(1), 49. https://doi.org/10.3390/horticulturae10010049

Galema, S., Male, D., Mbabazi, M., Mutambuka, M., Muzira, R., Nambooze, J., Ruma, D. H., Byakika, S., Muyanja, Ingram, J., & Dengerink, J. (2024). An overview of the Ugandan food system: Outcomes, drivers & activities. Wageningen Centre for Development Innovation. https://doi.org/10.18174/657503

Ganguly, P., & Banerjee, K. (2025). Pesticide in Food Chain: Impact and Regulation. In D. Mondal & M. M. Rahman (Eds.), Food Toxicity and Safety (pp. 59–76). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-4128-4_3

Gao, C., El-Sawah, A. M., Ali, D. F. I., Alhaj Hamoud, Y., Shaghaleh, H., & Sheteiwy, M. S. (2020). The Integration of Bio and Organic Fertilizers Improve Plant Growth, Grain Yield, Quality and Metabolism of Hybrid Maize (Zea mays L.). Agronomy, 10(3), 319. https://doi.org/10.3390/agronomy10030319

Gautam,A.K., Balkrishna,A., Sharma,N., Arya,V., & Khelwade,V. (2025). Effects of organic fertilizers on growth and yield potential of spinach. 3(2), 109–115.

Geisseler, D., Smith, R., Cahn, M., & Muramoto, J. (2021). Nitrogen mineralization from organic fertilizers and composts: Literature survey and model fitting. Journal of Environmental Quality, 50(6), 1325–1338. https://doi.org/10.1002/jeq2.20295

Ghimire, A., Dahal, M., & Karki, R. (2023). Hydroponics: An Innovative Approach to Urban Agriculture.

Gitau, K., Ambuko, J.L., Chemining'wa, G.N., & Owino, W. (2022). Effect of harvest stage and nitrogen fertilization on the postharvest shelf life of black nightshade (Solanum nigrum L.) and collard (Brassica oleracea var. Acephala L.).

Gonçalves, A., Goufo, P., Barros, A.I., Domínguez-Perles, R., Trindade, H., Rosa, E.A., Ferreira, L., & Rodrigues, M.A. (2016). Cowpea (Vigna unguiculata L. Walp), a renewed multipurpose crop for a more sustainable agri-food system: Nutritional advantages and constraints. 96(9), 2941–2951.

Government of Uganda. (2013). Uganda Vision 2040. https://www.npa.go.ug/uganda-vision-2040

Griengo,S.G., Bandera,A.D., & Magolama,A.A. (2023). Application of different fertilizer types and levels on vegetable production: A critical review.

Grobelnik Mlakar, S. (2012). Protein concentration and amino acid composition in grain amaranth (Amaranthus cruentus L.) as affected by sowing date and nitrogen fertilization. AFRICAN JOURNAL OF AGRICULTURAL RESEEARCH, 7(37). https://doi.org/10.5897/AJAR12.1117

Gruda, N. (2019). Increasing Sustainability of Growing Media Constituents and Stand-Alone Substrates in Soilless Culture Systems. Agronomy, 9(6), 298. https://doi.org/10.3390/agronomy9060298

Gruda, N. S. (2022a). Advances in Soilless Culture and Growing Media in Today's Horticulture—An Editorial. Agronomy, 12(11), 2773. https://doi.org/10.3390/agronomy12112773

Gruda, N. S. (2022b). Advances in Soilless Culture and Growing Media in Today's Horticulture—An Editorial. Agronomy, 12(11), 2773. https://doi.org/10.3390/agronomy12112773

Gruda, N., S. ,., & Fernández, J. A. (2022). Optimising Soilless Culture Systems and Alternative Growing Media to Current Used Materials. Horticulturae, 8(4), 292. https://doi.org/10.3390/horticulturae8040292

Gruda,N. (2018). Soilless plant cultivation systems. 297–327. https://doi.org/10.1007/978-981-13-0032-5_17

Gumisiriza, M. S., Kabirizi, J. M. L., Mugerwa, M., Ndakidemi, Patrick. A., & Mbega, E. R. (2022a). Can soilless farming feed urban East Africa? An assessment of the benefits and challenges of hydroponics in Uganda and Tanzania. Environmental Challenges, 6, 100413. https://doi.org/10.1016/j.envc.2021.100413

Gumisiriza, M. S., Kabirizi, J. M. L., Mugerwa, M., Ndakidemi, Patrick. A., & Mbega, E. R. (2022b). Can soilless farming feed urban East Africa? An assessment of the benefits and challenges of hydroponics in Uganda and Tanzania. Environmental Challenges, 6, 100413. https://doi.org/10.1016/j.envc.2021.100413

Gumisiriza, M. S., Ndakidemi, P. A., Nampijja, Z., & Mbega, E. R. (2023). Soilless urban gardening as a post covid-19 food security salvage technology: A study on the physiognomic response of lettuce to hydroponics in Uganda. Scientific African, 20, e01643. https://doi.org/10.1016/j.sciaf.2023.e01643

Guo, C., Yuan, X., Yan, F., Xiang, K., Wu, Y., Zhang, Q., Wang, Z., He, L., Fan, P., Yang, Z., Chen, Z., Sun, Y., & Ma, J. (2022). Nitrogen Application Rate Affects the Accumulation of Carbohydrates in Functional Leaves and Grains to Improve Grain Filling and Reduce the Occurrence of Chalkiness. Frontiers in Plant Science, 13, 921130. https://doi.org/10.3389/fpls.2022.921130

Hashemi, F., Mogensen, L., Smith, A. M., Larsen, S. U., & Knudsen, M. T. (2024). Greenhouse gas emissions from bio-based growing media: A life-cycle assessment. Science of The Total Environment, 907, 167977. https://doi.org/10.1016/j.scitotenv.2023.167977

Hashimi,A., Khan, M. A., & Rahman, S. (2019). Effect of organic fertilizers on growth and nutrient composition of spinach (Spinacia oleracea. 21(3), 45–52.

Helalya, A. A., Hassan, S. M., Craker, L. E., & Madya, E. (2020). Effects of growth-promoting bacteria on growth, yield and nutritional value of collard plants. 65(1), 77–82.

Hina, N. S. (2024). Global Meta-Analysis of Nitrate Leaching Vulnerability in Synthetic and Organic Fertilizers over the Past Four Decades. Water, 16(3), 457. https://doi.org/10.3390/w16030457

Hossain, M., & Ryu, K. (2018a). Effects of organic and inorganic fertilizers on lettuce (Lactuca sativa L.) and soil properties. SAARC Journal of Agriculture, 15(2), 93–102. https://doi.org/10.3329/sja.v15i2.35158

Hossain, M., & Ryu, K. (2018b). Effects of organic and inorganic fertilizers on lettuce (Lactuca sativa L.) and soil properties. SAARC Journal of Agriculture, 15(2), 93–102. https://doi.org/10.3329/sja.v15i2.35158

Howard, J. E., Villamil, M. B., & Riggins, C. W. (2022a). Amaranth as a natural food colorant source: Survey of germplasm and optimization of extraction methods for betalain pigments. Frontiers in Plant Science, 13, 932440. https://doi.org/10.3389/fpls.2022.932440

Howard, J. E., Villamil, M. B., & Riggins, C. W. (2022b). Amaranth as a natural food colorant source: Survey of germplasm and optimization of extraction methods for betalain pigments. Frontiers in Plant Science, 13, 932440. https://doi.org/10.3389/fpls.2022.932440

Ibrahim, M., Jaafar, H., Karimi, E., & Ghasemzadeh, A. (2013). Impact of Organic and Inorganic Fertilizers Application on the Phytochemical and Antioxidant Activity of Kacip Fatimah (Labisia pumila Benth). Molecules, 18(9), 10973–10988. https://doi.org/10.3390/molecules180910973

Ikiz, B., Dasgan, H. Y., & Gruda, N. S. (2024). Utilizing the power of plant growth promoting rhizobacteria on reducing mineral fertilizer, improved yield, and nutritional quality of Batavia lettuce in a floating culture. Scientific Reports, 14(1), 1616. https://doi.org/10.1038/s41598-024-51818-w

Imo, M. (2012). Analysis of Nutritional Interactions in Cropping Systems. In P. Sharma (Ed.), Crop Production Technologies. InTech. https://doi.org/10.5772/28508

Inyang, U. E. (2016). Nutrient Content of Four Lesser – Known Green Leafy Vegetables Consumed by Efik and Ibibio People in Nigeria. Nigerian Journal of Basic and Applied Sciences, 24(1), 1. https://doi.org/10.4314/njbas.v24i1.1

Inzule, S. C. (2011). Influence of nitrogen fertilization and plant age on yield, quality and storability of kale and collard (Brassica oleracea* var. Acephala)* (Master's thesis, University of Nairobi).

Irin, I. J., & Hasanuzzaman, M. (2024). Organic Amendments: Enhancing Plant Tolerance to Salinity and Metal Stress for Improved Agricultural Productivity. Stresses, 4(1), 185–209. https://doi.org/10.3390/stresses4010011

Isah, T. (2019). Stress and defense responses in plant secondary metabolites production. Biological Research, 52(1), 39. https://doi.org/10.1186/s40659-019-0246-3

Issa-Zacharia, A., Majaliwa, N. K., Nyamete, F. A., & Chove, L. M. (2024). Diversity of Underutilised Vegetables in Africa and Their Potential in the Reduction of Micronutrient Deficiency: A Review. World Journal of Food Science and Technology. https://doi.org/10.11648/j.wjfst.20240801.11

Ivanišová, E., Kačániová, M., A. Savitskaya, T., & D. Grinshpan, D. (2021). Medicinal Herbs: Important Source of Bioactive Compounds for Food Industry. In R. Shabir Ahmad (Ed.), Herbs and Spices—New Processing Technologies. IntechOpen. https://doi.org/10.5772/intechopen.98819

Jama, B., Palm, C. A., Buresh, R. J., Niang, A., Gachengo, C., Nziguheba, G., & Amadalo, B. (2000). Tithonia diversifolia as a green manure for soil fertility improvement in western Kenya: A review. Agroforestry Systems, 49(2), 201–221. https://doi.org/10.1023/A:1006339025728

Jaya, S. & Prased, R. (2014). Soil-based cultivation and its impact on mineral accumulation in leafy vegetables. 6(2), 112–120.

Jayathilake, Visvanathan,R., Deen, A., Bangamuwage,R., Jayawardana, B.C., Nammi, S., & Liyanage, R. (2018). Cowpea: An overview on its nutritional facts and health benefits. 98(13).

Jiménez-Aguilar, D. M., & Grusak, M. A. (2015). Evaluation of Minerals, Phytochemical Compounds and Antioxidant Activity of Mexican, Central American, and African Green Leafy Vegetables. Plant Foods for Human Nutrition, 70(4), 357–364. https://doi.org/10.1007/s11130-015-0512-7

Jiménez-Aguilar, D. M., & Grusak, M. A. (2017). Minerals, vitamin C, phenolics, flavonoids and antioxidant activity of Amaranthus leafy vegetables. Journal of Food Composition and Analysis, 58, 33–39. https://doi.org/10.1016/j.jfca.2017.01.005

Jindo, K., Sánchez-Monedero, M. A., Mastrolonardo, G., Audette, Y., Higashikawa, F. S., Silva, C. A., Akashi, K., & Mondini, C. (2020). Role of biochar in promoting circular economy in the agriculture sector. Part 2: A review of the biochar roles in growing media, composting and as soil amendment. Chemical and Biological Technologies in Agriculture, 7(1), 16. https://doi.org/10.1186/s40538-020-00179-3

Johnson, M., McElhenney, W., & Egnin, M. (2019). Influence of Green Leafy Vegetables in Diets with an Elevated ω-6:ω-3 Fatty Acid Ratio on Rat Blood Pressure, Plasma Lipids, Antioxidant Status and Markers of Inflammation.

Joshi, D., Nainabasti, A., Bhandari, R., Awasthi, P., Banjade, D., Malla, S., & Subedi, B. (2022). A review on soilless cultivation: The hope of urban agriculture. Archives of Agriculture and Environmental Science, 7(3), 473–481. https://doi.org/10.26832/24566632.2022.0703022

Juárez-Chairez, M.F., Meza-Márquez, O.G., Márquez-Flores, Y.K., & Jiménez-Martínez, C. (2020). Potential anti-inflammatory effects of legumes: A review. 128, 21588–22169.

Junedi, H., Suryanto, S., & Syukria, H. (2022). Effect of coffee husk compost to increase peanut yield in inceptisol. 1005.

Kabunga, N., Ghosh, S., & Griffiths, J. K. (2014). Can Smallholder Fruit and Vegetable Production Systems Improve Household Food Security and Nutritional Status of Women? Evidence from Rural Uganda. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2483967

Kalaivanan, D., Selvakumar, G., & Carolin Rathinakumari, A. (2023a). Soilless Cultivation to Secure the Vegetable Demand of Urban and Peri-Urban Population. In M. Turan, S. Argin, E. Yildirim, & A. Güneş (Eds.), Recent Research and Advances in Soilless Culture. IntechOpen. https://doi.org/10.5772/intechopen.102695

Kalaivanan, D., Selvakumar, G., & Carolin Rathinakumari, A. (2023b). Soilless Cultivation to Secure the Vegetable Demand of Urban and Peri-Urban Population. In M. Turan, S. Argin, E. Yildirim, & A. Güneş (Eds.), Recent Research and Advances in Soilless Culture. IntechOpen. https://doi.org/10.5772/intechopen.102695

Karmakar, S., Adhikary, M. M., Gangopadhyay, A., & Brahmachari, K. (2015). Impact of Vermicomposting Agricultural Waste Management vis-à-vis Soil Health Care. 8, 99–104.

Kebrom, T. H., Woldesenbet, S., Bayabil, H. K., Garcia, M., Gao, M., Ampim, P., Awal, R., & Fares, A. (2019). Evaluation of phytotoxicity of three organic amendments to collard greens using the seed germination bioassay. Environmental Science and Pollution Research, 26(6), 5454–5462. https://doi.org/10.1007/s11356-018-3928-4

Kiggundu, N., & Sittamukyoto, J. (2019a). Pryloysis of Coffee Husks for Biochar Production. Journal of Environmental Protection, 10(12), 1553–1564. https://doi.org/10.4236/jep.2019.1012092

Kiggundu, N., & Sittamukyoto, J. (2019b). Pryloysis of Coffee Husks for Biochar Production. Journal of Environmental Protection, 10(12), 1553–1564. https://doi.org/10.4236/jep.2019.1012092

Kim, E., Cui, J., Zhang, G., & Lee, Y. (2022). Physiological Effects of Green-Colored Food-Derived Bioactive Compounds on Cardiovascular and Metabolic Diseases. Applied Sciences, 12(4), 1879. https://doi.org/10.3390/app12041879

Kiran, D., Yadav, B. L., Yadav, Mamta., & Choudhary, Meena. (2018). Impact of sodium and iron levels on yield, nutrient content and uptake by cowpea (Vigna unguiculata L.). Legume Research. 43(4). https://doi.org/10.18805/LR-4004

Klubicová, K., Szabová, M., Skultety, L., Libiaková, G., & Hricová, A. (2016). Revealing the seed proteome of the health benefitting grain amaranth (Amaranthus cruentus L.). Chemical Papers, 70(10). https://doi.org/10.1515/chempap-2016-0065

Kratky, B. A. (2009). THREE NON-CIRCULATING HYDROPONIC METHODS FOR GROWING LETTUCE. Acta Horticulturae, (843), 65–72. https://doi.org/10.17660/ActaHortic.2009.843.6

Kriticos, J. M., & Kriticos, D. J. (2021). Pretty (and) invasive: The potential global distribution of Tithonia diversifolia under current and future climates. Invasive Plant Science and Management, 14(4), 205–213. https://doi.org/10.1017/inp.2021.29

Kuca, K., Patocka, J., Kumar, V., & Dhalaria, R. (Eds.). (2025). Medicinal Plants and Their Bioactives in Human Diseases. Springer Nature Switzerland. https://doi.org/10.1007/978-3-032-01356-9

Kumar, R., Singh, J., Sharma, R. K., Kumar, S., & Pandey, A. K. (2024). Optimizing growth and nutrient uptake of spinach (Spinacia oleracea) in hydroponic systems through varied fertilizer concentrations. International Journal of Advanced Biochemistry Research, 8(8S), 690–694. https://doi.org/10.33545/26174693.2024.v8.i8Sj.1911

Kyomuhendo, P., Tenywa, M. M., Semalulu, O., Lenssen, A. W., Yost, R. S., Mazur, R. E., Kyebogola, S., & Goettsch, L. H. (2018). Limiting nutrients for bean production on contrasting soil types of Lake Victoria Crescent of Uganda. African Crop Science Journal, 26(4), 543. https://doi.org/10.4314/acsj.v26i4.8

Lai, B., Li, Z., & Li, J. (2025). Cruciferous vegetables intake and risk of colon cancer: A dose–response meta-analysis. BMC Gastroenterology, 25(1), 575. https://doi.org/10.1186/s12876-025-04163-9

Lakhiar, I. A., Yan, H., Syed, T. N., Zhang, C., Shaikh, S. A., Rakibuzzaman, Md., & Vistro, R. B. (2025a). Soilless Agricultural Systems: Opportunities, Challenges, and Applications for Enhancing Horticultural Resilience to Climate Change and Urbanization. Horticulturae, 11(6), 568. https://doi.org/10.3390/horticulturae11060568

Lakhiar, I. A., Yan, H., Syed, T. N., Zhang, C., Shaikh, S. A., Rakibuzzaman, Md., & Vistro, R. B. (2025b). Soilless Agricultural Systems: Opportunities, Challenges, and Applications for Enhancing Horticultural Resilience to Climate Change and Urbanization. Horticulturae, 11(6), 568. https://doi.org/10.3390/horticulturae11060568

Latvia University of Life Sciences and Technologies, Kunkulberga, D., Linina, A., & Ruza, A. (2019). Effect of nitrogen fertilization on protein content and rheological properties of winter wheat wholemeal. 88–92. https://doi.org/10.22616/FoodBalt.2019.026

Lawrence, B. T., & Melgar, J. C. (2023). Annual compost amendments can replace synthetic fertilizer, improve soil moisture, and ensure tree performance during peach orchard establishment in a humid subtropical climate. Frontiers in Plant Science, 14, 1172038. https://doi.org/10.3389/fpls.2023.1172038

Li, X., Gao, Y., Cui, Z., Zhang, T., Chen, S., Xiang, S., Jia, L., Yan, B., Wang, Y., Guo, L., & Wu, B. (2024). Optimized nitrogen and potassium fertilizers application increases stem lodging resistance and grain yield of oil flax by enhancing lignin biosynthesis. Journal of Integrative Agriculture, S2095311924003277. https://doi.org/10.1016/j.jia.2024.09.006

Liem, D. G., & Russell, C. G. (2019). The Influence of Taste Liking on the Consumption of Nutrient Rich and Nutrient Poor Foods. Frontiers in Nutrition, 6, 174. https://doi.org/10.3389/fnut.2019.00174

Liu, L., Zheng, X., Wei, X., Kai, Z., & Xu, Y. (2021). Excessive application of chemical fertilizer and organophosphorus pesticides induced total phosphorus loss from planting causing surface water eutrophication. Scientific Reports, 11(1), 23015. https://doi.org/10.1038/s41598-021-02521-7

Liu, Y., Lan, X., Hou, H., Ji, J., Liu, X., & Lv, Z. (2024). Multifaceted Ability of Organic Fertilizers to Improve Crop Productivity and Abiotic Stress Tolerance: Review and Perspectives. Agronomy, 14(6), 1141. https://doi.org/10.3390/agronomy14061141

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., & Gattinger, A. (2017). Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. PLOS ONE, 12(7), e0180442. https://doi.org/10.1371/journal.pone.0180442

Luna, M. C., Martínez-Sánchez, A., Selma, M. V., Tudela, J. A., Baixauli, C., & Gil, M. I. (2013). Influence of nutrient solutions in an open-field soilless system on the quality characteristics and shelf life of fresh-cut red and green lettuces (Lactuca sativa L.) in different seasons. Journal of the Science of Food and Agriculture, 93(2), 415–421. https://doi.org/10.1002/jsfa.5777

Mabhaudhi, T., Chimonyo, V. G. P., Hlahla, S., Massawe, F., Mayes, S., Nhamo, L., & Modi, A. T. (2019). Prospects of orphan crops in climate change. Planta, 250(3), 695–708. https://doi.org/10.1007/s00425-019-03129-y

Machado, R. M. A., Alves-Pereira, I., Lourenço, D., & Ferreira, R. M. A. (2020). Effect of organic compost and inorganic nitrogen fertigation on spinach growth, phytochemical accumulation and antioxidant activity. Heliyon, 6(9), e05085. https://doi.org/10.1016/j.heliyon.2020.e05085

Maffia, A., Oliva, M., Marra, F., Mallamaci, C., Nardi, S., & Muscolo, A. (2025). Humic Substances: Bridging Ecology and Agriculture for a Greener Future. Agronomy, 15(2), 410. https://doi.org/10.3390/agronomy15020410

Magalhães, D., Gonçalves, R., Rodrigues, C. V., Rocha, H. R., Pintado, M., & Coelho, M. C. (2024). Natural Pigments Recovery from Food By-Products: Health Benefits towards the Food Industry. Foods, 13(14), 2276. https://doi.org/10.3390/foods13142276

Maheswari, M., Murthy, A. N. G., & Shanker, A. K. (2017a). Nitrogen Nutrition in Crops and Its Importance in Crop Quality. In The Indian Nitrogen Assessment (pp. 175–186). Elsevier. https://doi.org/10.1016/B978-0-12-811836-8.00012-4

Maheswari, M., Murthy, A. N. G., & Shanker, A. K. (2017b). Nitrogen Nutrition in Crops and Its Importance in Crop Quality. In The Indian Nitrogen Assessment (pp. 175–186). Elsevier. https://doi.org/10.1016/B978-0-12-811836-8.00012-4

Mampholo, B. M., Maboko, M. M., Soundy, P., & Sivakumar, D. (2018). Variety-specific responses of lettuce grown in a gravel-film technique closed hydroponic system to N supply on yield, morphology, phytochemicals, mineral content and safety. Journal of Integrative Agriculture, 17(11), 2447–2457. https://doi.org/10.1016/S2095-3119(18)62007-6

Manoharan, C. (2021). Scope of Organic Farming Vegetable Cultivation.

Market.us. (2025). Organic Fruits and Vegetables Market Growth Forecast 2024—2034. https://market.us/report/organic-fruits-and-vegetables-market

Martínez-Alcántara, B., Martínez-Cuenca, M.-R., Bermejo, A., Legaz, F., & Quiñones, A. (2016). Liquid Organic Fertilizers for Sustainable Agriculture: Nutrient Uptake of Organic versus Mineral Fertilizers in Citrus Trees. PLOS ONE, 11(10), e0161619. https://doi.org/10.1371/journal.pone.0161619

Martirosyan, D. (2025). Functional Food Science and Bioactive Compounds. Bioactive Compounds in Health and Disease - Online ISSN: 2574-0334; Print ISSN: 2769-2426, 8(6), 218–229. https://doi.org/10.31989/bchd.v8i6.1667

Maseko, I., Mabhaudhi, T., Tesfay, S., Araya, H., Fezzehazion, M., & Plooy, C. (2017). African Leafy Vegetables: A Review of Status, Production and Utilization in South Africa. Sustainability, 10(1), 16. https://doi.org/10.3390/su10010016

Mdlambuzi, T., Tsubo, M., & Muchaonyerwa, P. (2021). Short-term effects of selected organic fertilizer sources on carbon dioxide fluxes and soil quality. Journal of Environmental Quality, 50(2), 312–323. https://doi.org/10.1002/jeq2.20174

Mead, B. R., Duncombe, T., Gillespie, R., Pugh, N., & Hardman, C. A. (2024). Does urban agriculture contribute to food security, and how might this be achieved? Proceedings of the Nutrition Society, 83(3), 195–203. https://doi.org/10.1017/S0029665124002209

Michelon, D., Qureshi, M. A., & Otieno, D. (2021). Nitrogen fertilization strategies for leafy vegetables under soilless systems. 12(3), 112–124.

Mila, K. J., Hassan, J., Hasan, Md. F., Alfagham, A. T., Ali, L., Islam, Md. S., Zubayer, Md., Gomasta, J., Ozaki, Y., Siddiqui, M. H., Khalid, F., & Mondal, Md. F. (2024). Nutritional composition, bioactive compounds and antioxidant potentiality of some indigenous vegetables consumed in Bangladesh. Scientific Reports, 14(1), 27699. https://doi.org/10.1038/s41598-024-78625-7

Minich, D. M. (2019). A Review of the Science of Colorful, Plant-Based Food and Practical Strategies for "Eating the Rainbow." Journal of Nutrition and Metabolism, 2019, 1–19. https://doi.org/10.1155/2019/2125070

Mndzebele, B., Ncube, B., Fessehazion, M., Mabhaudhi, T., & Modi, A. T. (2023). Assessment of the effects of NPK fertilizer on edible yield and agro-biological parameters in a cowpea–amaranth intercrop. Frontiers in Sustainable Food Systems, 7, 1210984. https://doi.org/10.3389/fsufs.2023.1210984

Mogale, E. T., Ayisi, K. K., Munjonji, L., & Kifle, Y. G. (2023a). Biological Nitrogen Fixation of Cowpea in a No-Till Intercrop under Contrasting Rainfed Agro-Ecological Environments. Sustainability, 15(3), 2244. https://doi.org/10.3390/su15032244

Mogale, E. T., Ayisi, K. K., Munjonji, L., & Kifle, Y. G. (2023b). Biological Nitrogen Fixation of Cowpea in a No-Till Intercrop under Contrasting Rainfed Agro-Ecological Environments. Sustainability, 15(3), 2244. https://doi.org/10.3390/su15032244

Mohamed, T., Tanko, H., & Tahir, C. (2018). The Prospects of Organic Agriculture and Yield Improvement in the 21st Century.

Mohanapriya, R., Kalpana, R., & Aravinth, K. V. (2022). Quality Enhancement of Fruits and Vegetables through Organic Cultivation: A Review. Agricultural Reviews, (Of). https://doi.org/10.18805/ag.R-2351

Montgomery, M., & Srinivasan, A. (2019). Epigenetic Gene Regulation by Dietary Compounds in Cancer Prevention. Advances in Nutrition, 10(6), 1012–1028. https://doi.org/10.1093/advances/nmz046

Moorthi & D'Souza. (2025).). Nutritional enhancement of spinach under hydroponic NPK regimes. 29(1), 33–34.

Moorthi,S. (2023). Biochemistry, nutritional composition, and health benefits of spinach (Spinacia oleracea): A comprehensive review. 11(2), 4889.

Moussa Mohamadou, Stephanie Beaudelaine Kengni, Steve Takoukam Toukam, Albert Ngakou, & Fernand-Nestor Tchuenguem Fohouo. (2023). The cumulative use of compost teas and rhizobia against Megalurothrips jostetti for yield improvement in field grown cowpea at Ngaoundere (Cameroon). International Journal of Science and Research Archive, 8(2), 085–101. https://doi.org/10.30574/ijsra.2023.8.2.0182

Mulatu, G., & Bayata, A. (2024). Vermicompost as Organic Amendment: Effects on Some Soil Physical, Biological Properties and Crops Performance on Acidic Soil: A Review. Frontiers in Environmental Microbiology, 10(4), 66–73. https://doi.org/10.11648/j.fem.20241004.11

Naik, P. K., Dhawaskar, B. D., Fatarpekar, D. D., Chakurkar, E. B., Swain, B. K., & Singh, N. P. (2016). Nutrient Changes with the Growth of Hydroponics Cowpea (Vigna unguiculata) Sprouts. Indian Journal of Animal Nutrition, 33(3), 357. https://doi.org/10.5958/2231-6744.2016.00064.5

National Planning Authority. (2020). Third National Development Plan (NDP III) 2020/21—2024/25},. https://www.npa.go.ug/ndp-iii/

Ngidi, M. S. C. (2023). The Role of Traditional Leafy Vegetables on Household Food Security in Umdoni Municipality of the KwaZulu Natal Province, South Africa. Foods, 12(21), 3918. https://doi.org/10.3390/foods12213918

North-West University, Private Bag X2046, Mmabatho 2735, South Africa, Uzoh, I., Babalola, O., & University of Nigeria, Nsukka. (2020). Review on increasing iron availability in soil and its content in cowpea (Vigna unguiculata) by plant growth promoting rhizobacteria. African Journal of Food, Agriculture, Nutrition and Development, 20(03), 15779–15799. https://doi.org/10.18697/ajfand.91.18530

Nutrition value org. (2024). Collards, raw nutrition facts and analysis. https://www.nutritionvalue.org/Collards%2C_raw_nutritional_value.html

Ojo, O. D., Akinrinde, E. A., & Akoroda, M. O. (2010). RESIDUAL EFFECTS OF PHOSPHORUS SOURCES IN GRAIN AMARANTH PRODUCTION. Journal of Plant Nutrition, 33(5), 770–783. https://doi.org/10.1080/01904160903577648

Oke, D. B., Tewe, O. O., & Fetuga, B. L. (2021). THE NUTRIENT COMPOSITION OF SOME COWPEA VARIETIES. Nigerian Journal of Animal Production, 22(1), 32–36. https://doi.org/10.51791/njap.v22i1.2024

Okoma, R. N., Omuse, E. R., Mutyambai, D. M., Beesigamukama, D., Murongo, M. F., Subramanian, S., & Chidawanyika, F. (2025). An assessment of vegetable production constraints, trait preferences and willingness to adopt sustainable intensification options in Kenya and Uganda. Frontiers in Sustainable Food Systems, 9, 1471333. https://doi.org/10.3389/fsufs.2025.1471333

Orsomando, G., Agostinelli, S., Bramucci, M., Cappellacci, L., Damiano, S., Lupidi, G., Maggi, F., Ngahang Kamte, S. L., Biapa Nya, P. C., Papa, F., Petrelli, D., Quassinti, L., Sorci, L., Vitali, L. A., & Petrelli, R. (2016). Mexican sunflower (Tithonia diversifolia, Asteraceae) volatile oil as a selective inhibitor of Staphylococcus aureus nicotinate mononucleotide adenylyltransferase (NadD). Industrial Crops and Products, 85, 181–189. https://doi.org/10.1016/j.indcrop.2016.03.003

Osumah,A.B., Akinyemi,O.S., & Eguagie,E.I. (2023). Evaluation of amaranth dry matter yield and its nutrient uptake under the influence of some organic fertilizers and NPK 20:10:10. https://hortson.org.ng/images/Journals/2023volume/Osumah_et_al_2023_authentic_compressed.pdf

Othman,Y., Bataineh,Y., Al-Ajlouni,M., Alsmairat,N., Shiyab,S., Al-Qarallah,B., & St Hilaire,R. (2019). Soilless culture: Management of growing substrate, water, nutrient, salinity, microorganism and product quality. 28(4A), 3249–3260.

Ozer, H., Ozdemir, N., Ates, A., Koklu, R., Ozturk Erdem, S., & Ozdemir, S. (2024). Circular Utilization of Coffee Grounds as a Bio-Nutrient through Microbial Transformation for Leafy Vegetables. Life, 14(10), 1299. https://doi.org/10.3390/life14101299

Panta, S., & Parajulee, D. (2021). Integrated Nutrient Management (INM) in Soil and Sustainable Agriculture. International Journal of Applied Sciences and Biotechnology, 9(3), 160–165. https://doi.org/10.3126/ijasbt.v9i3.39275

Partey, S. T., Thevathasan, N. V., Zougmoré, R. B., & Preziosi, R. F. (2016). Improving maize production through nitrogen supply from ten rarely-used organic resources in Ghana. Agroforestry Systems. https://doi.org/10.1007/s10457-016-0035-8

Paul, T., Saha, B. K., Mohiuddin, K., Debi, M., & Uddin, M. K. (2024). Enhanced Efficiency Organo-Mineral Nitrogen Fertilizer improves Yield and Quality of Red Amaranth. Journal of Science and Technology Research, 5(1), 37–44. https://doi.org/10.3329/jscitr.v5i1.73995

Pedreira, B. C., Yasuoka, J. I., Barros, I. T. M. D., Helwig, D., Farney, J. K., & Sassenrath, G. F. (2023). Management strategies to improve forage accumulation and nutritive value in crabgrass hayfields. The Journal of Agricultural Science, 161(4), 581–588. https://doi.org/10.1017/S0021859623000485

Pelu, J., Tyasmoro, S. Y., & Maghfoer, Moch. D. (2020). Effect bulking agent on composting mexican sunflower (Tithonia diversifolia L) biomass and utilization on pak choi production. AGROMIX, 11(1), 49–65. https://doi.org/10.35891/agx.v11i1.1906

Peng, H., Chen, Y., Yan, Z., & Han, W. (2016). Stage-dependent stoichiometric homeostasis and responses of nutrient resorption in Amaranthus mangostanus to nitrogen and phosphorus addition. Scientific Reports, 6, 37219. https://doi.org/10.1038/srep37219

Pereira, H., Deuchande, T., Fundo, J. F., Leal, T., Pintado, M. E., & Amaro, A. L. (2024). Painting the picture of food colouring agents: Near-ubiquitous molecules of everyday life – A review. Trends in Food Science & Technology, 143, 104249. https://doi.org/10.1016/j.tifs.2023.104249

Pokhare, N. P. (2023). Effect of Organic Manures and Fertilizers on Growth and Yield of Knol Khol (Brassica oleracea var. Gongylodes L.) in the Western Terai Region of Nepal. International Journal of Agriculture Environment and Biotechnology, 16(3). https://doi.org/10.30954/0974-1712.03.2023.5

Puteri, A. R., Setyowati, N., Fahrurrozi, & Muktamar, Z. (2021). Growth and yield of sweet corn (Zea mays L. Saccharata) as affected by incubation time of preparation for tithonia (Tithonia diversifolia) enriched liquid organic fertilizer. IOP Conference Series: Earth and Environmental Science, 637(1), 012090. https://doi.org/10.1088/1755-1315/637/1/012090

Qureshi, F., Wani, A., Bashir, U., Malik, M. A., & Mir, S. A. (2022). RESPONSE OF FARMYARD MANURE AND INORGANIC NITROGEN ON VEGETATIVE GROWTH, LEAF YIELD AND QUALITY OF KALE (BRASSICA OLERACEAVARACEPHALA) IN TEMPERATE REGION OF KASHMIR VALLEY. https://doi.org/10.5281/ZENODO.7215225

Rajesh Devisetti & Jamuna Prakash. (2020). Comparative assessment of organic and non-organic – chickpea and cowpea, nutritional composition and antinutrients upon germination. World Journal of Advanced Research and Reviews, 8(2), 262–270. https://doi.org/10.30574/wjarr.2020.8.2.0432

Ramaiyan, B., Kour, J., Nayik, G. A., Anand, N., & Alam, M. S. (2020). Spinach (Spinacia oleracea L.). In G. A. Nayik & A. Gull (Eds.), Antioxidants in Vegetables and Nuts—Properties and Health Benefits (pp. 159–173). Springer Singapore. https://doi.org/10.1007/978-981-15-7470-2_8

Ranka Junge, & Gertrud Buchenrieder. (2025). Addressing Hidden Hunger Through Soilless Cultivation of Vegetables.

Rashid, M., Yousaf, Z., Din, A., Munawar, M., Aftab, A., Riaz, N., Younas, A., Alaraidh, I. A., Okla, M. K., & AbdElgawad, H. (2022). Assessment of Mineral Nutrient Efficiency in Genetically Diverse Spinach Accessions by Biochemical and Functional Marker Strategies. Frontiers in Plant Science, 13, 889604. https://doi.org/10.3389/fpls.2022.889604

Rastogi, A., & Shukla, S. (2013a). Amaranth: A New Millennium Crop of Nutraceutical Values. Critical Reviews in Food Science and Nutrition, 53(2), 109–125. https://doi.org/10.1080/10408398.2010.517876

Rastogi, A., & Shukla, S. (2013b). Amaranth: A New Millennium Crop of Nutraceutical Values. Critical Reviews in Food Science and Nutrition, 53(2), 109–125. https://doi.org/10.1080/10408398.2010.517876

Rathnayake, D., Creber, H., Van Poucke, R., Sohi, S., Meers, E., Mašek, O., & Ronsse, F. (2021). Biochar from sawmill residues: Characterization and evaluation for its potential use in the horticultural growing media. Biochar, 3(2), 201–212. https://doi.org/10.1007/s42773-021-00092-4

Reisinger, A. J., Bean, E. Z., Clark, M., Levine, A. J., & Wilson, P. C. (2025). Fertilizer management approaches influence nutrient leaching from residential landscapes. Journal of Environmental Quality, 54(1), 289–302. https://doi.org/10.1002/jeq2.20657

Renju, C., Zhang, P., Li, L., Xiao, J., Su, Z., & Xiao, T. (2014). Analysis of Nutrition of Collard Green Grown in China. 5, 1–5.

Research Institute (Ifpri), I. F. P. (2016). Hidden hunger: Approaches to tackling micronutrient deficiencies (0 ed.). International Food Policy Research Institute. https://doi.org/10.2499/9780896295889_04

Rietra, R. P. J. J., Heinen, M., Dimkpa, C. O., & Bindraban, P. S. (2017). Effects of Nutrient Antagonism and Synergism on Yield and Fertilizer Use Efficiency. Communications in Soil Science and Plant Analysis, 48(16), 1895–1920. https://doi.org/10.1080/00103624.2017.1407429

Roberts, J. L., & Moreau, R. (2016). Functional properties of spinach (Spinacia oleracea L.) phytochemicals and bioactives. Food & Function, 7(8), 3337–3353. https://doi.org/10.1039/C6FO00051G

Ronner, E., Van Reemst, L., & Van Der Poel, M. (2023). Opportunities for organic agriculture in Uganda: Commissioned by the Agricultural Counsellor of the Dutch Ministry of Agriculture, Nature and Food Quality, based in Kampala, Uganda. Wageningen Environmental Research. https://doi.org/10.18174/644578

Rubaihayo, E. B. (2002). The contribution of indigenous vegetables to household food security. 44. http://documents.worldbank.org/curated/en/396501468342229695/pdf/24775-Replacement-file-IKNT44.pdf

Sambo, P., Nicoletto, C., Giro, A., Pii, Y., Valentinuzzi, F., Mimmo, T., Lugli, P., Orzes, G., Mazzetto, F., Astolfi, S., Terzano, R., & Cesco, S. (2019). Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. Frontiers in Plant Science, 10, 923. https://doi.org/10.3389/fpls.2019.00923

San Martin Ruiz, M., Reiser, M., & Kranert, M. (2021). Composting and Methane Emissions of Coffee By-Products.

Sande, T. J., Tindwa, H. J., Alovisi, A. M. T., Shitindi, M. J., & Semoka, J. M. (2024). Enhancing sustainable crop production through integrated nutrient management: A focus on vermicompost, bio-enriched rock phosphate, and inorganic fertilizers – a systematic review. Frontiers in Agronomy, 6, 1422876. https://doi.org/10.3389/fagro.2024.1422876

Sarma, U., & Tr, B. (2024a). Dietary phytonutrients in common green leafy vegetables and the significant role of processing techniques on spinach: A review. Food Production, Processing and Nutrition, 6(1), 10. https://doi.org/10.1186/s43014-023-00192-7

Sarma, U., & Tr, B. (2024b). Dietary phytonutrients in common green leafy vegetables and the significant role of processing techniques on spinach: A review. Food Production, Processing and Nutrition, 6(1), 10. https://doi.org/10.1186/s43014-023-00192-7

Sattar, M., Saeed, F., Afzaal, M., Rasheed, A., Asif, A., Sharif, S., Hussain, M., Asad Ur Rehman, H., Raza, M. A., Munir, H., & Al Jbawi, E. (2024a). An overview of the nutritional and therapeutic properties of amaranth. International Journal of Food Properties, 27(1), 263–272. https://doi.org/10.1080/10942912.2024.2304266

Sattar, M., Saeed, F., Afzaal, M., Rasheed, A., Asif, A., Sharif, S., Hussain, M., Asad Ur Rehman, H., Raza, M. A., Munir, H., & Al Jbawi, E. (2024b). An overview of the nutritional and therapeutic properties of amaranth. International Journal of Food Properties, 27(1), 263–272. https://doi.org/10.1080/10942912.2024.2304266

Sauman Ham, J., Zahra Tunn, A., Nuraini, A., & Budiarto, R. (2022). Production of G0 'Median' Potato on Different Media Composition and Fertilizer Method. Asian Journal of Plant Sciences, 21(2), 312–320. https://doi.org/10.3923/ajps.2022.312.320

Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry – A review. European Journal of Horticultural Science, 83, 280–293. https://doi.org/10.17660/eJHS.2018/83.5.2

Schwarz, D., Franken, P., Krumbein, A., Kläring, H.-P., & Bar-Yosef, B. (2009). NUTRIENT MANAGEMENT IN SOILLESS CULTURE IN THE CONFLICT OF PLANT, MICROORGANISM, CONSUMER AND ENVIRONMENTAL DEMANDS. Acta Horticulturae, (843), 27–34. https://doi.org/10.17660/ActaHortic.2009.843.1

Scrase, F. M., Sinclair, F. L., Farrar, J. F., Pavinato, P. S., & Jones, D. L. (2019). Mycorrhizas improve the absorption of non-available phosphorus by the green manure Tithonia diversifolia in poor soils. Rhizosphere, 9, 27–33. https://doi.org/10.1016/j.rhisph.2018.11.001

Senarathne, S. H. S., Atapattu, A. J., Raveendra, T., Mensah, S., & Dassanayake, K. B. (2019a). Biomass allocation and growth performance of Tithonia diversifolia (Hemsl.) A. Gray in coconut plantations in Sri Lanka. Agroforestry Systems, 93(5), 1865–1875. https://doi.org/10.1007/s10457-018-0290-y

Senarathne, S. H. S., Atapattu, A. J., Raveendra, T., Mensah, S., & Dassanayake, K. B. (2019b). Biomass allocation and growth performance of Tithonia diversifolia (Hemsl.) A. Gray in coconut plantations in Sri Lanka. Agroforestry Systems, 93(5), 1865–1875. https://doi.org/10.1007/s10457-018-0290-y

Shaji, H., Chandran, V., & Mathew, L. (2021). Organic fertilizers as a route to controlled release of nutrients. In Controlled Release Fertilizers for Sustainable Agriculture (pp. 231–245). Elsevier. https://doi.org/10.1016/B978-0-12-819555-0.00013-3

Shiferaw, B., Prasanna, B. M., Hellin, J., & Bänziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. Food Security, 3(3), 307–327. https://doi.org/10.1007/s12571-011-0140-5

Shikha Markam. (2022). Nutritive values and importance of green leafy vegetables in human diet: A review.

Shingo, G. Y., & Ventura, M. U. (2009). Produção de couve brassica oleracea L. var. Acephala com adubação mineral e orgânica. Semina: Ciências Agrárias, 30(3), 589. https://doi.org/10.5433/1679-0359.2009v30n3p589

Si, C., Shi, C., Liu, H., Zhan, X., & Liu, Y. (2018). Effects of nitrogen forms on carbohydrate metabolism and storage-root formation of sweet potato. Journal of Plant Nutrition and Soil Science, 181(3), 419–428. https://doi.org/10.1002/jpln.201700297

Silva, A.C., Santos, D.D., Junior, D.L., Silva, P.B., Santos, R.C., & Siviero, A. (2018). Cowpea: A Strategic Legume Species for Food Security and Health.

Silva, G. A. D. S., Silva, A. R. D., Oliveira, E. G. D., & Almeida-Bezerra, J. W. (2020). Ethnopharmacological Potential of Tithonia diversifolia (Hemsl) A. Gray. Research, Society and Development, 9(10), e2339108370. https://doi.org/10.33448/rsd-v9i10.8370

Silva, M. M., Reboredo, F. H., & Lidon, F. C. (2022). Food Colour Additives: A Synoptical Overview on Their Chemical Properties, Applications in Food Products, and Health Side Effects. Foods (Basel, Switzerland), 11(3), 379. https://doi.org/10.3390/foods11030379

Singh, A., Dubey, P. K., Chaurasiya, R., Mathur, N., Kumar, G., Bharati, S., & Abhilash, P. C. (2018). Indian spinach: An underutilized perennial leafy vegetable for nutritional security in developing world. Energy, Ecology and Environment, 3(3), 195–205. https://doi.org/10.1007/s40974-018-0091-1

Singh, A., Mal, D., Swain, A. R., & Mohapatra, A. (2024). Exploring the Nutritional and Medicinal Potential of Indian Spinach (Basella rubra L.): A Comprehensive Review. Journal of Advances in Biology & Biotechnology, 27(7), 437–446. https://doi.org/10.9734/jabb/2024/v27i71004

Singh, N., Samarth, R. M., Vashishth, A., & Pareek, A. (2024). Amaranthus as a potential dietary supplement in sports nutrition. CyTA - Journal of Food, 22(1), 2375253. https://doi.org/10.1080/19476337.2024.2375253

Soriano-García, M., & Saraid Aguirre-Díaz, I. (2020). Nutritional Functional Value and Therapeutic Utilization of Amaranth. In V. Y. Waisundara (Ed.), Nutritional Value of Amaranth. IntechOpen. https://doi.org/10.5772/intechopen.86897

Sossa-Vihotogbe, A., Anihouvi, B., Akissoe, H., Amadji, L., & Hounhouigan, D. (2013). Effect of organic and mineral fertilization on proximate composition of three leafy vegetables harvested at different periods. International Journal of Biological and Chemical Sciences, 7(1), 271. https://doi.org/10.4314/ijbcs.v7i1.23

Sudharani P, Kishan K.P.C, & Shambhavi Shakhya. (2024). PROXIMATE ANALYSIS OF SPINACH (Spinacia oleracea): NUTRITIONAL AND BUSINESS IMPLICATIONS. EPRA International Journal of Research & Development (IJRD), 275–279. https://doi.org/10.36713/epra15662

Swanson, E. O., Carlson, J. L., Perkus, L. A., Grossman, J., Rogers, M. A., Erwin, J. E., Slavin, J. L., & Rosen, C. J. (2022). Nutrient and Nitrate Composition of Greenhouse-Grown Leafy Greens: A Trial Comparison Between Conventional and Organic Fertility Treatments. Frontiers in Sustainable Food Systems, 6, 811995. https://doi.org/10.3389/fsufs.2022.811995

Szulc, P., Ambroży-Deręgowska, K., Waligóra, H., Mejza, I., Grześ, S., Zielewicz, W., & Wróbel, B. (2021). Dry Matter Yield of Maize (Zea mays L.) as an Indicator of Mineral Fertilizer Efficiency. Plants, 10(3), 535. https://doi.org/10.3390/plants10030535

Tamale, J., Hüppi, R., Griepentrog, M., Turyagyenda, L. F., Barthel, M., Doetterl, S., Fiener, P., & Van Straaten, O. (2021). Nutrient limitations regulate soil greenhouse gas fluxes from tropical forests: Evidence from an ecosystem-scale nutrient manipulation experiment in Uganda. SOIL, 7(2), 433–451. https://doi.org/10.5194/soil-7-433-2021

Tamilselvan, K., Sundarajan, S., Ramakrishna, S., Amirul, A.-A. A., & Vigneswari, S. (2024). Sustainable valorisation of coffee husk into value added product in the context of circular bioeconomy: Exploring potential biomass-based value webs. Food and Bioproducts Processing, 145, 187–202. https://doi.org/10.1016/j.fbp.2024.03.008

Tei, F., De Neve, S., De Haan, J., & Kristensen, H. L. (2020). Nitrogen management of vegetable crops. Agricultural Water Management, 240, 106316. https://doi.org/10.1016/j.agwat.2020.106316

Thakur, M., & Modi, V. K. (2024). Biocolorants in food: Sources, extraction, applications and future prospects. Critical Reviews in Food Science and Nutrition, 64(14), 4674–4713. https://doi.org/10.1080/10408398.2022.2144997

Toimbayeva, D., Saduakhasova, S., Kamanova, S., Kiykbay, A., Tazhina, S., Temirova, I., Muratkhan, M., Shaimenova, B., Murat, L., Khamitova, D., & Ospankulova, G. (2025). Prospects for the Use of Amaranth Grain in the Production of Functional and Specialized Food Products. Foods, 14(9), 1603. https://doi.org/10.3390/foods14091603

Tuxun, A., Xiang, Y., Shao, Y., Son, J. E., Yamada, M., Yamada, S., Tagawa, K., Baiyin, B., & Yang, Q. (2025). Soilless Cultivation: Precise Nutrient Provision and Growth Environment Regulation Under Different Substrates. Plants, 14(14), 2203. https://doi.org/10.3390/plants14142203

Ubroda, W. (2024). Mastering the Kratky Method: A comprehensive guide to passive hydroponic food production. https://greeneryretail.com/blog/kratky-method-guide

USDA Foreign Agricultural Service. (2024). U.S. Agricultural Export Yearbook 2024. https://www.fas.usda.gov/data

Uusiku, N. P., Oelofse, A., Duodu, K. G., Bester, M. J., & Faber, M. (2010a). Nutritional value of leafy vegetables of sub-Saharan Africa and their potential contribution to human health: A review. Journal of Food Composition and Analysis, 23(6), 499–509. https://doi.org/10.1016/j.jfca.2010.05.002

Uusiku, N. P., Oelofse, A., Duodu, K. G., Bester, M. J., & Faber, M. (2010b). Nutritional value of leafy vegetables of sub-Saharan Africa and their potential contribution to human health: A review. Journal of Food Composition and Analysis, 23(6), 499–509. https://doi.org/10.1016/j.jfca.2010.05.002

Uusiku, N. P., Oelofse, A., Duodu, K. G., Bester, M. J., & Faber, M. (2010c). Nutritional value of leafy vegetables of sub-Saharan Africa and their potential contribution to human health: A review. Journal of Food Composition and Analysis, 23(6), 499–509. https://doi.org/10.1016/j.jfca.2010.05.002

Vidal, N. P., Pham, H. T., Manful, C., Pumphrey, R., Nadeem, M., Cheema, M., Galagedara, L., Leke-Aladekoba, A., Abbey, Lord, & Thomas, R. (2018). The use of natural media amendments to produce kale enhanced with functional lipids in controlled environment production system. Scientific Reports, 8(1), 14771. https://doi.org/10.1038/s41598-018-32866-5

Villagran, E., Espitia, J. J., Amado, G., Rodriguez, J., Gomez, L., Velasquez, J. F., Gil, R., Baeza, E., Aguilar, C. E., Akrami, M., & Arias, L. A. (2025). CO2 Enrichment in Protected Agriculture: A Systematic Review of Greenhouses, Controlled Environment Systems, and Vertical Farms—Part 2. Sustainability, 17(7), 2809. https://doi.org/10.3390/su17072809

Vivas, E. A., Castillo, H. S. V., & Acosta, E. G. (2025). Physicochemical and Structural Characterization of Coffee Husks for Sustainable Applications in Biodegradable Materials. Journal of Natural Fibers, 22(1), 2453489. https://doi.org/10.1080/15440478.2025.2453489

Wan, C., Gao, L., Wang, J., Lei, X., Tao, J., Feng, B., & Gao, J. (2023). Effects of nitrogen fertilizer on protein synthesis, accumulation, and physicochemical properties in common buckwheat. The Crop Journal, 11(3), 941–950. https://doi.org/10.1016/j.cj.2023.01.002

Wang, H., Zhang, X., Zhang, G., Fang, Y., Hou, H., Lei, K., & Ma, Y. (2023). Regulation of Density and Fertilization on Crude Protein Synthesis in Forage Maize in a Semiarid Rain-Fed Area. Agriculture, 13(3), 715. https://doi.org/10.3390/agriculture13030715

Wang, X., Wang, K., Yin, T., Zhao, Y., Liu, W., Shen, Y., Ding, Y., & Tang, S. (2021). Nitrogen Fertilizer Regulated Grain Storage Protein Synthesis and Reduced Chalkiness of Rice Under Actual Field Warming. Frontiers in Plant Science, 12, 715436. https://doi.org/10.3389/fpls.2021.715436

Waseem, M., Akhtar, S., Manzoor, M. F., Mirani, A. A., Ali, Z., Ismail, T., Ahmad, N., & Karrar, E. (2021a). Nutritional characterization and food value addition properties of dehydrated spinach powder. Food Science & Nutrition, 9(2), 1213–1221. https://doi.org/10.1002/fsn3.2110

Waseem, M., Akhtar, S., Manzoor, M. F., Mirani, A. A., Ali, Z., Ismail, T., Ahmad, N., & Karrar, E. (2021b). Nutritional characterization and food value addition properties of dehydrated spinach powder. Food Science & Nutrition, 9(2), 1213–1221. https://doi.org/10.1002/fsn3.2110

Wei, L., Li, J., Qu, K., Chen, H., Wang, M., Xia, S., Cai, H., Long, X.-E., Miao, Y., & Liu, D. (2024). Organic fertilizer application promotes the soil nitrogen cycle and plant starch and sucrose metabolism to improve the yield of Pinellia ternata. Scientific Reports, 14(1), 12722. https://doi.org/10.1038/s41598-024-63564-0

WHFoods. (2025). Collard greens nutrition and health benefits. https://whfoods.org/nutrition/collard-greens/

Wiggins, Z., Akaeze, O., Nandwani, D., & Witcher, A. (2020a). Substrate Properties and Fertilizer Rates on Yield Responses of Lettuce in a Vertical Growth System. Sustainability, 12(16), 6465. https://doi.org/10.3390/su12166465

Wiggins, Z., Akaeze, O., Nandwani, D., & Witcher, A. (2020b). Substrate Properties and Fertilizer Rates on Yield Responses of Lettuce in a Vertical Growth System. Sustainability, 12(16), 6465. https://doi.org/10.3390/su12166465

Willer, H., Schlatter, B., & Czech Organic. (2023). The World Organic Agriculture. Statistics and Emerging Trends 2023. Zenodo. https://doi.org/10.5281/ZENODO.7572890

World Bank. (2018). Developing the agri-food system for inclusive economic growth: Uganda fact sheet. World Bank Group.

Yadav, A., & Yadav, K. (2024). From humble beginnings to nutritional powerhouse: The rise of amaranth as a climate-resilient superfood. Tropical Plants, 3(1), 0–0. https://doi.org/10.48130/tp-0024-0037

Yamini, V., Singh, K., Antar, M., & El Sabagh, A. (2025). Sustainable cereal production through integrated crop management: A global review of current practices and future prospects. Frontiers in Sustainable Food Systems, 9, 1428687. https://doi.org/10.3389/fsufs.2025.1428687

Yang, T., Samarakoon, U., Altland, J., & Ling, P. (2024). Influence of Electrical Conductivity on Plant Growth, Nutritional Quality, and Phytochemical Properties of Kale (Brassica napus) and Collard (Brassica oleracea) Grown Using Hydroponics. Agronomy, 14(11), 2704. https://doi.org/10.3390/agronomy14112704

Yao, X., Wang, X., Zheng, S., Zhao, H., Ju, J., & Wang, C. (2024). Research on Composting of Garden Waste and Its Application in Cultivation Substrates. Sustainability, 16(18), 8216. https://doi.org/10.3390/su16188216

Yeasmin, S., Noman, M., Betto, Z. S., Rahman, T., Sarly, S. P., Islam, A. K. M. M., & Anwar, Md. P. (2025). Impact of Organic and Inorganic Sources of Nitrogen on Soil Fertility, Nitrogen Use Efficiency, and Carbon Accumulation Potential Under Subtropical Rice-Based Cropping Patterns in Farmers' Fields. Nitrogen, 6(3), 86. https://doi.org/10.3390/nitrogen6030086

Zhang, J., Yue, Y., Sha, Z., Kirumba, G., Zhang, Y., Bei, Z., & Cao, L. (2014). Spinach-irrigating and fertilizing for optimum quality, quantity, and economy. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 64(7), 590–598. https://doi.org/10.1080/09064710.2014.936489

Zhu, F. (2023). Amaranth proteins and peptides: Biological properties and food uses. Food Research International, 164, 112405. https://doi.org/10.1016/j.foodres.2022.112405

Zoca, S. M., Penn, C. J., Rosolem, C. A., Alves, A. R., Neto, L. O., & Martins, M. M. (2014). Coffee processing residues as a soil potassium amendment. 3, 155–165.

APPENDICES

Appendix A: Conference attendance

The following conferences were attended during the course of this research:

Conference 1: "Effects of soilless potting growth media composition and fertilizer regimes on morphological traits of leafy vegetables" at the "5th Global virtual Conference on Climate Change" held during July 28th -29th 2025 in the UK

Conference 2: "Effects of Organic and Inorganic Fertilizers on Yield and Nutrient Composition of Leafy Vegetables Grown in Soilless Potting Mixes" at the "International Conference on Agriculture, Forest, Food, Food Sciences and Technologies (ICAF3T-25) " held on 20th -21st August 2025 in Algers, Algeria

Conference 3: "Effects of soilless potting growth media composition and fertilizer regimes on morphological traits of leafy vegetables" at the "The 12th International Conference on Agriculture 2025" held on 22nd -23rd 2025 in Bangkok, Thailand


AGRICO

THE INTERNATIONAL INSTITUTE OF KNOWLEDGE MANAGEMENT

TIIKM

This is to Certify that

ROSELINE CHEMUTAI

has Participated as a **Physical Oral Presenter**

at

THE 12TH INTERNATIONAL CONFERENCE ON AGRICULTURE 2025

"INNOVATION LIGHTENS THE FUTURE WAY FOR GLOBAL SUSTAINABLE FOOD SECURITY"

22nd – 23rd September 2025 | Bangkok, Thailand

Prof. Dr. Samih Abubaker Conference Co-Chair	ASSOC. PROF. SIVA K. BALASUNDRAM Conference Co-Chair	PROF. SAMAN SENEWEERA Conference Co-Chair	Mr. Isanka P. Gamage Conference Convener

Appendix B**:** Layout of the Experiment and the pictures of the four selected leafy vegetables

Layout of the experiment pots in the greenhouse

Spinach at different stages of grow


Replication 3


Replication 4

Cowpea vegetable at different stages of growth

Amaranth young shoots

Collard vegetable at different stages of growth

Appendix C: Vegetable samples in the Laboratory

Oven dried samples for different nutrient laboratory analyses