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Substrate–nutrient Interactions in Hydroponic Production of Super Habanero Pepper: Global Perspectives and Implications for Nigeria

Eriegha Avwerosuo [a*] and Ojobor A. Smart [a]

[a] *Department of Agronomy, Delta State University, Abraka, Nigeria.*

Authors' contributions

This work was carried out in collaboration between both authors. Author EA conceived and designed the study, conducted the literature review, and wrote the first draft of the manuscript. Author OAS contributed to the critical review of the manuscript, refinement of content, and overall supervision. Both authors read and approved the final manuscript.

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Review Article

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Abstract

The growing demand for high-quality horticultural produce, alongside constraints associated with conventional soil-based agriculture, has intensified interest in hydroponic systems as a sustainable alternative for crop production. Super Habanero pepper (*Capsicum chinense* Jacq.), a high-value crop known for its pungency and market appeal, presents significant potential for hydroponic cultivation. However, achieving optimal productivity depends largely on effective root zone management, particularly the interactions between growing substrates and nutrient composition. This review synthesises current knowledge on substrate–nutrient interactions in hydroponic systems and their combined effects on the growth, yield, and fruit quality of Super Habanero pepper. It critically examines the physicochemical properties of commonly used substrates, including organic and inorganic media, and evaluates their roles in regulating water

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**Corresponding author: E-mail: avwerosuod4th@gmail.com;*

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retention, aeration, and nutrient availability. The review also analyses nutrient solution formulation, with emphasis on macronutrient and micronutrient balance, electrical conductivity, and pH, and how these factors influence plant physiological responses. Given the limited availability of crop-specific studies, evidence from related *Capsicum* species is integrated to provide a comprehensive understanding. The review highlights that substrate–nutrient interactions exert synergistic effects on nutrient uptake efficiency and overall plant performance, significantly influencing yield and fruit quality. It further discusses recent advances in hydroponic technologies, including innovative substrates and precision nutrient management strategies. Particular attention is given to the challenges and opportunities for adapting these systems in Nigeria, where hydroponic production remains underdeveloped. This review provides a framework for optimising hydroponic pepper production and offers practical insights for enhancing productivity and sustainability in Nigeria and similar environments.

Keywords: Hydroponics; substrate types; nutrient composition; super habanero pepper; growing media.

1. Introduction

The increasing demand for high-quality horticultural produce, driven by rapid population growth, urbanisation, and changing dietary preferences, has intensified the need for efficient and sustainable agricultural production systems (Sashika et al., 2024). Conventional soil-based agriculture is increasingly constrained by factors such as land degradation, declining soil fertility, climate variability, and limited access to arable land, particularly in developing countries (Grover et al., 2024). In Nigeria, these challenges are further compounded by rapid urban expansion, oil-related environmental disturbances in regions such as the Niger Delta, and the growing pressure on available agricultural land (Ilemobayo, 2021). These limitations have necessitated the adoption of innovative cultivation techniques capable of enhancing productivity while minimising environmental impacts. Hydroponic systems, which involve the cultivation of plants in nutrient-enriched solutions without the use of soil, have emerged as a promising alternative for intensive crop production (Lakhiar et al., 2025). These systems offer several advantages, including efficient water and nutrient utilisation, reduced incidence of soil-borne diseases, and the ability to produce crops year-round under controlled environmental conditions. In Nigeria, hydroponics is gradually gaining attention among researchers, entrepreneurs, and urban farmers as a viable approach to improving food security and supporting commercial vegetable production in space-limited environments.

Pepper (*Capsicum spp*.) is one of the most widely cultivated and economically important vegetable crops globally, valued for its culinary uses, nutritional benefits, and industrial applications (Anaya-Esparza et al., 2021). Among the various pepper types, the Super Habanero pepper is notable for its high pungency, distinctive flavour, and increasing market demand in both local and international markets. The cultivation of Super Habanero pepper in hydroponic systems presents significant opportunities for enhancing yield, improving fruit quality, and ensuring consistent production. However, achieving optimal growth and productivity in hydroponic systems depends largely on the effective management of the root zone environment, particularly the selection of suitable substrates and the formulation of appropriate nutrient solutions. Substrates play a critical role in hydroponic production by providing physical support for plant roots and influencing water retention, aeration, and nutrient availability (Zhao et al., 2022). Common substrates such as coco peat, rice husk, sawdust, perlite, and rockwool exhibit varying physicochemical properties that can significantly affect root development and plant performance. In the Nigerian context, the use of locally available and cost-effective substrates such as rice husk and sawdust is of particular interest, given the need to reduce production costs and promote sustainable agricultural practices. At the same time, nutrient composition, including the balance and concentration of essential macro and micronutrients, is fundamental to plant physiological processes such as photosynthesis, enzyme activity, flowering, and fruit development.

Recent advances in hydroponic research have increasingly emphasised that plant growth and yield are not determined solely by substrate type or nutrient composition in isolation, but rather by the interactions between these factors within the root zone. Substrate properties can influence nutrient retention, ion exchange, and the mobility of dissolved elements, while nutrient formulations can alter substrate chemistry, including pH and electrical conductivity (Schafer and Lerner, 2022). These interactions ultimately affect nutrient uptake efficiency, root health, and overall plant productivity. Despite this growing recognition, many studies have examined substrate and nutrient effects independently, resulting in fragmented knowledge and limited understanding of their combined influence on hydroponic crop performance (Palmitessa et al., 2024). In Nigeria and similar developing regions, there is a notable lack of comprehensive reviews that synthesise current advances in substrate–nutrient interactions, particularly in relation to pepper production systems. This gap limits the ability of researchers, practitioners, and agribusiness stakeholders to make informed decisions regarding the optimisation of hydroponic systems for improved productivity and sustainability. Furthermore, the scarcity of crop-specific information for Super Habanero pepper necessitates the integration of findings from related *Capsicum* species to provide a more holistic understanding of its production requirements. This review, therefore, aims to synthesise existing knowledge on substrate–nutrient interactions in hydroponic systems, with a particular emphasis on their effects on the growth and yield of Super Habanero pepper. Specifically, the review examines the characteristics and performance of different substrate types, evaluates the role of nutrient composition and formulation, and analyses how their interactions influence nutrient availability, uptake, and plant response. In addition, the paper highlights current advances in hydroponic technologies, identifies key challenges and knowledge gaps, and proposes future research directions for optimising hydroponic pepper production, particularly within the Nigerian context.

2. Overview of Hydroponic Systems in Pepper Production

Hydroponic technology has evolved significantly over the past few decades as a response to the limitations of conventional soil-based agriculture. Its application in vegetable production, particularly for high-value crops such as pepper (*Capsicum spp*.), has expanded due to its capacity to provide controlled growth conditions, optimise resource use, and enhance productivity. Understanding the principles, types, and suitability of hydroponic systems is essential for evaluating how substrate–nutrient interactions influence plant performance.

2.1 Principles of Hydroponics

Hydroponics refers to the cultivation of plants in a nutrient solution, with or without the use of an inert growing medium to support the root system (Jan et al., 2020). In this system, all essential nutrients required for plant growth are supplied in soluble form, allowing precise control over nutrient concentration, composition, and availability. The fundamental principle of hydroponics lies in maintaining an optimal root zone environment where water, nutrients, and oxygen are supplied in adequate proportions (Sheikh, 2006). Unlike soil systems, where nutrient availability is influenced by complex biological and chemical interactions, hydroponic systems allow direct regulation of key parameters such as pH, electrical conductivity, and dissolved oxygen. This controlled environment enhances nutrient uptake efficiency and reduces losses due to leaching or fixation.

Hydroponic systems offer several advantages, including efficient water use, reduced dependence on arable land, and minimised incidence of soil-borne pests and diseases (Visen et al., 2024). These benefits are particularly relevant in regions such as Nigeria, where erratic rainfall patterns, soil degradation, and land-use pressures pose significant challenges to conventional agriculture (Iwuchukwu et al., 2023). However, hydroponics also presents limitations, including high initial investment costs, technical complexity, and the need for continuous monitoring and management.

2.2 Types of Hydroponic Systems

Hydroponic systems can be broadly classified based on how nutrient solutions are delivered to plant roots (Sambo et al., 2019). The most commonly used systems in pepper production include the Nutrient Film Technique (NFT), Deep Water Culture (DWC), drip systems, ebb and flow systems, and aeroponics. The NFT Technique involves the continuous flow of a thin film of nutrient solution over the roots, ensuring a constant supply of nutrients and oxygen. This system is efficient in water and nutrient use but requires careful management to prevent system failure. The DWC system suspends plant roots in a nutrient solution that is continuously aerated. This method provides stable nutrient availability and is relatively simple to operate, making it suitable for small-scale and experimental setups.

Drip systems deliver nutrient solutions directly to the base of each plant through emitters, often in combination with substrates such as coco peat or perlite (Atzori et al., 2021). This system is widely used in commercial production due to its flexibility and suitability for a variety of crops, including peppers (Pimenta et al., 2016). Ebb and flow systems, also known as flood and drain systems, periodically flood the root zone with nutrient solution and then drain it away, allowing for intermittent nutrient supply and aeration. In Nigeria, the adoption of hydroponic systems is still at a developing stage, with drip and substrate-based systems being more common due to their adaptability to locally available materials and relatively lower technical requirements. The choice of system often influences substrate selection and nutrient management practices, thereby affecting overall plant performance. Aeroponics, on the other hand, represents a more advanced hydroponic technique in which plant roots are suspended in air and intermittently misted with a nutrient solution. This system provides exceptional oxygen availability to the root zone and can enhance nutrient uptake efficiency and growth rates; however, it requires high technical precision and constant monitoring to prevent root desiccation and system failure (Kumar et al., 2024).

2.3 Suitability of Hydroponics for Pepper Cultivation

Pepper plants are well-suited to hydroponic cultivation due to their relatively high nutrient demand, sensitivity to soil-borne diseases, and responsiveness to controlled environmental conditions (Lakhia et al., 2025). Hydroponic systems enable precise regulation of nutrient supply and environmental factors, which are critical for achieving optimal vegetative growth, flowering, and fruit development in pepper crops. Studies have shown that hydroponically grown peppers often exhibit improved growth rates, higher yields, and better fruit quality compared to those grown in soil (Giuffrida and Leonardi, 2012). Enhanced control over nutrient availability allows for the optimisation of key growth stages, while improved root aeration promotes efficient nutrient uptake and reduces the risk of root diseases.

Super Habanero pepper, which is valued for its pungency and commercial appeal, hydroponic production offers the advantage of consistent fruit quality and uniformity (Bhattarai et al., 2025). This is particularly important for meeting market standards and ensuring competitiveness in both local and export markets. In Nigeria, where demand for fresh and processed pepper products is high, hydroponic cultivation presents a viable opportunity for increasing production efficiency and supporting agribusiness development. However, the success of hydroponic pepper production is highly dependent on the effective management of substrates and nutrient solutions. The interaction between these factors plays a critical role in determining nutrient availability, root health, and overall plant performance. As such, a comprehensive understanding of hydroponic systems provides the foundation for analysing the influence of substrate–nutrient interactions on the growth and yield of Super Habanero pepper.

3. Growing Substrates in Hydroponic Systems

Growing substrates constitute a fundamental component of hydroponic production systems, particularly in media-based cultivation where plants are not grown directly in nutrient solution. Although hydroponics is defined as soilless culture, substrates provide a critical interface between the plant root system and the nutrient solution (Tuxun et al., 2025). They influence root anchorage, water and nutrient dynamics, aeration, and microbial activity within the root zone. In hydroponic pepper production, including Super Habanero pepper, substrate selection is a key determinant of crop performance because it directly affects physiological processes such as root respiration, nutrient uptake efficiency, and overall plant vigour.

3.1 Functions of Substrates

The role of substrates in hydroponic systems extends beyond simple physical support for plants. One of the primary functions is mechanical stabilisation of the root system, ensuring that plants remain upright throughout their growth cycle (Khelalfa and Khelalfa, 2024). This is particularly important for pepper crops, which develop woody stems and heavy fruit loads during production stages (Gisbert-Mullor et al., 2023). Without adequate support, lodging and structural stress can negatively affect yield and fruit quality. Another critical function of substrates is the regulation of water availability within the root zone. Substrates act as reservoirs that retain irrigation water and gradually release it to plant roots. The balance between water retention and drainage is essential because excessive moisture can lead to oxygen deficiency, while insufficient moisture can limit nutrient transport and uptake. Therefore, an ideal hydroponic substrate maintains a stable moisture level while still allowing periodic drainage to prevent waterlogging.

Substrates also play a significant role in root zone aeration. Oxygen availability is essential for root respiration, which provides energy for nutrient absorption and metabolic activity. Poorly aerated substrates can lead to hypoxic conditions, resulting in reduced root growth, impaired nutrient uptake, and increased susceptibility to root diseases (Lee et al., 2014). This is particularly relevant in tropical environments such as Nigeria, where high temperatures can intensify oxygen depletion in poorly structured media. Substrates also influence nutrient dynamics through adsorption, desorption, and buffering effects. Some substrates can temporarily hold nutrient ions and release them gradually, thereby stabilising nutrient supply to plants. This buffering capacity helps reduce nutrient leaching and improves fertiliser use efficiency. However, substrates with high adsorption capacity may also bind certain nutrients too strongly, reducing their availability to plants if not properly managed (Tang et al., 2023). Substrates can also influence the microbial environment of the root zone. Organic substrates in particular support microbial colonisation, which can enhance nutrient cycling and promote plant growth through beneficial plant–microbe interactions. However, this microbial activity can also lead to variability in nutrient availability depending on decomposition rates and environmental conditions.

3.2 Types of Substrates Used in Hydroponics

Hydroponic substrates are generally categorised into organic, inorganic, and synthetic or engineered materials, each with distinct physical and chemical properties that influence plant growth performance. Organic substrates include materials such as coco peat, rice husk, sawdust, and peat-based materials (Younis et al., 2022). These substrates are derived from plant or agricultural waste products and are widely valued for their availability and sustainability. In Nigeria and many other developing countries, agricultural by-products such as rice husk and sawdust are particularly important due to their low cost and accessibility. Coco peat, derived from coconut husks, is widely used in commercial hydroponics due to its excellent water retention capacity, moderate aeration, and relatively stable structure over time. However, organic substrates may undergo decomposition during crop cycles, leading to changes in physical properties and potential nutrient immobilisation.

Inorganic substrates include perlite, vermiculite, gravel, and rockwool (Kadioğlu, 2023). These materials are generally chemically inert and provide stable physical conditions throughout the cropping cycle. Perlite is highly porous and enhances aeration, while vermiculite has a higher water and nutrient retention capacity due to its layered structure. Rockwool is widely used in commercial hydroponic production due to its uniformity, sterility, and high-water holding capacity, although its disposal raises environmental concerns. Inorganic substrates are particularly useful in systems requiring high consistency and controlled nutrient delivery. Emerging substrates such as biochar, coconut fibre blends, and engineered composites are gaining attention in hydroponic research. Biochar, in particular, has shown potential for improving nutrient retention, enhancing microbial activity, and increasing water holding capacity. These novel substrates are being explored as sustainable alternatives that can reduce environmental impact while maintaining or improving crop productivity (Sahoo and Dash, 2025). The selection of substrate type is often influenced by cost, availability, crop requirements, and system design. In developing regions such as Nigeria, substrate choice is frequently guided by affordability and local availability, which makes agricultural waste-based substrates more common than imported commercial materials.

3.3 Physicochemical Properties of Substrates

The performance of a substrate in hydroponic systems is largely determined by its physicochemical characteristics, which regulate water, air, and nutrient dynamics within the root zone (Balliu et al., 2021). Key properties include porosity, bulk density, water holding capacity, pH, electrical conductivity, and cation exchange capacity. Porosity refers to the proportion of void spaces within the substrate that can hold air and water. High total porosity generally improves aeration but may reduce water retention if macropores dominate. The balance between macropores and micropores is therefore critical for maintaining optimal root zone conditions (Zhang et al., 2022). Bulk density influences both root penetration and substrate handling. Low bulk density substrates are easier for root expansion and reduce physical resistance to root growth, while high bulk density materials may restrict root development but provide better structural stability.

Water holding capacity determines how much water a substrate can retain after drainage. Substrates with high water holding capacity reduce irrigation frequency but may increase the risk of oxygen deficiency if not properly aerated (Othman et al., 2019). Conversely, low water-holding substrates require more frequent irrigation but improve oxygen availability. The pH of the substrate affects nutrient solubility and availability. Most hydroponic crops, including pepper, perform best within a slightly acidic to neutral pH range. Deviations from optimal pH can lead to nutrient lockout or toxicity. Electrical conductivity provides an indication of total soluble salt concentration within the substrate. High EC levels may indicate excessive nutrient accumulation, which can lead to osmotic stress and reduced water uptake by plants (Roosta, 2024).

Cation exchange capacity (CEC) reflects the ability of a substrate to retain positively charged nutrient ions such as potassium, calcium, and magnesium. Substrates with higher CEC can buffer nutrient fluctuations and improve nutrient stability, which is particularly beneficial in systems with variable irrigation or nutrient supply schedules.

3.4 Effects of Substrate Type on Plant Growth and Yield

Substrate type has a profound influence on plant growth, development, and yield in hydroponic systems due to its effects on root zone environment and nutrient availability (Balliu et al., 2021). Differences in physical structure and chemical properties among substrates can lead to significant variability in root architecture, nutrient uptake efficiency, and physiological performance. In pepper production, substrates such as coco peat and perlite are often associated with improved vegetative growth and higher yields due to their balanced water retention and aeration properties. These substrates promote extensive root development, which enhances nutrient absorption and supports vigorous shoot growth. In contrast, substrates with poor aeration or excessive water retention may lead to reduced root activity and lower productivity.

Fruit development and yield in Super Habanero pepper are also influenced by substrate conditions. Adequate nutrient and water supply during the flowering and fruit set stages is essential for achieving optimal fruit size, pungency, and uniformity. Substrates that support stable moisture and nutrient availability tend to produce more consistent yields and higher-quality fruits (Romero-Viacava and Tenorio-Bautista, 2023). In the Nigerian context, the use of locally available substrates such as rice husk and sawdust offers economic advantages but may present variability in performance due to differences in particle size, decomposition rate, and nutrient interaction behaviour. This variability underscores the importance of proper substrate processing and management to ensure consistency in hydroponic production systems.

4. Nutrient Composition in Hydroponic Systems

Nutrient composition is a central determinant of plant growth and productivity in hydroponic systems, where plants rely entirely on externally supplied nutrient solutions for their mineral requirements (Thakur et al., 2023). Unlike soil-based systems, where nutrient availability is mediated by complex physical, chemical, and biological processes, hydroponics allows direct control over the type, concentration, and balance of nutrients delivered to the plant root zone. This precise control offers significant advantages but also requires careful management to avoid nutrient imbalances, deficiencies, or toxicities.

In hydroponic pepper production, including Super Habanero pepper, nutrient composition plays a crucial role in regulating physiological processes such as vegetative growth, flowering, fruit development, and metabolite synthesis (González-Cortés et al., 2023). The effectiveness of nutrient supply is further influenced by its interaction with the growing substrate, which can modify nutrient availability, retention, and uptake dynamics. Therefore, understanding nutrient composition is essential for optimising hydroponic systems and maximising crop performance.

4.1 Essential Plant Nutrients

Plants require a range of essential mineral nutrients for growth and development, broadly classified into macronutrients and micronutrients based on the quantities required. Macronutrients include nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Nitrogen is a key component of amino acids, proteins, and chlorophyll, making it essential for vegetative growth and photosynthesis. Phosphorus plays a vital role in energy transfer through ATP and is critical for root development and flowering. Potassium regulates osmotic balance, enzyme activation, and stress tolerance, and is particularly important for fruit development and quality in pepper crops (Zewide and Melash, 2021). Calcium contributes to cell wall structure and membrane stability, while magnesium is a central component of chlorophyll and is involved in photosynthetic processes. Sulfur is required for the synthesis of certain amino acids and proteins.

Micronutrients, although required in smaller quantities, are equally important for plant health. These include iron, zinc, manganese, copper, boron, and molybdenum. Iron is essential for chlorophyll synthesis and electron transport, while zinc and manganese are involved in enzyme activation. Boron plays a role in cell wall formation and reproductive development, and molybdenum is important for nitrogen metabolism. In hydroponic systems, the absence of soil means that all these nutrients must be supplied in appropriate concentrations and ratios (Sagwal et al., 2023). Any imbalance can quickly manifest as deficiency or toxicity symptoms, affecting plant growth and yield.

4.2 Nutrient Solution Formulation

Nutrient solution formulation involves the preparation of balanced mixtures of essential nutrients in forms that are readily available for plant uptake. Standard hydroponic nutrient solutions are typically designed to meet the general requirements of crops, but adjustments are often necessary to suit specific plant species, growth stages, and environmental conditions. The balance between nutrients is critical, as interactions among elements can influence their uptake and utilisation (Wang et al., 2025). For example, excessive nitrogen may promote vegetative growth at the expense of flowering and fruiting, while inadequate potassium can reduce fruit quality and yield. Similarly, imbalances between calcium and magnesium can affect membrane stability and nutrient transport.

The management of pH and electrical conductivity (EC) is central to nutrient formulation. pH influences nutrient solubility and availability, with most hydroponic crops performing optimally within a slightly acidic range. Electrical conductivity reflects the total concentration of dissolved salts in the nutrient solution and serves as an indicator of nutrient strength. Maintaining appropriate EC levels is essential to avoid osmotic stress or nutrient deficiency (Sulaiman et al., 2025). In Nigeria, the formulation of nutrient solutions can present practical challenges due to limited access to high-quality fertilisers and hydroponic inputs. As a result, some producers rely on locally available fertiliser blends, which may not always provide optimal nutrient balance. This underscores the need for standardised nutrient formulations adapted to local conditions and resource availability.

4.3 Nutrient Dynamics in Hydroponics

Nutrient dynamics in hydroponic systems refer to the processes governing the availability, movement, and uptake of nutrients within the root zone. These dynamics are influenced by factors such as nutrient concentration, solution flow, root activity, and interactions with substrates. In hydroponics, nutrients are supplied in dissolved ionic forms, making them readily available for plant uptake (Carvalho et al., 2018). However, their mobility and availability can be affected by changes in pH, temperature, and solution composition. For example, fluctuations in pH can alter the solubility of micronutrients such as iron and manganese, potentially leading to deficiencies even when nutrients are present in sufficient quantities. Nutrient uptake occurs through both passive and active mechanisms. Passive uptake is driven by concentration gradients and transpiration, while active uptake involves energy-dependent transport processes within root cells. The efficiency of nutrient uptake is influenced by root health, oxygen availability, and the physical properties of the substrate.

In substrate-based hydroponic systems, nutrient dynamics are further modified by interactions with the growing medium (Tuxun et al., 2025). Substrates can retain, release, or immobilise nutrients, thereby affecting their availability over time. For instance, organic substrates may temporarily immobilise nitrogen during decomposition, while substrates with high cation exchange capacity can buffer nutrient fluctuations. Environmental conditions, particularly temperature and humidity, also play a role in nutrient dynamics. In tropical regions such as Nigeria, high temperatures can accelerate nutrient uptake rates but may also increase the risk of nutrient imbalances and solution instability if not properly managed.

4.4 Effects of Nutrient Composition on Growth and Yield

Nutrient composition has a direct and significant impact on plant growth, development, and yield in hydroponic systems. The availability and balance of nutrients influence key physiological processes, including cell division, photosynthesis, enzyme activity, and reproductive development (Sapkota et al., 2019). During the vegetative stage, adequate nitrogen supply promotes leaf expansion and biomass accumulation, which are essential for establishing a strong photosynthetic capacity. However, excessive nitrogen can delay flowering and reduce fruit set. Phosphorus is critical during early growth stages for root development, while potassium becomes increasingly important during flowering and fruiting stages, where it contributes to fruit size, colour, and quality. In pepper crops, including Super Habanero pepper, nutrient composition strongly influences yield components such as the number of fruits per plant, fruit weight, and overall productivity. Potassium and calcium are particularly important for fruit development and quality, affecting attributes such as firmness, shelf life, and resistance to physiological disorders.

Micronutrients also play essential roles in maintaining plant health and productivity. Deficiencies in micronutrients can lead to reduced growth, chlorosis, and impaired reproductive development, ultimately affecting yield (Abbas et al., 2021). In the Nigerian context, achieving optimal nutrient composition in hydroponic systems is often challenged by variability in input quality, water source composition, and technical expertise. These factors can lead to inconsistencies in nutrient supply, highlighting the importance of proper nutrient management practices and capacity building for hydroponic producers. The effects of nutrient composition on plant performance are closely linked to substrate characteristics. The interaction between nutrient solutions and substrates influences nutrient retention, availability, and uptake efficiency, making it necessary to consider these factors together rather than in isolation. This interaction forms the basis for optimising hydroponic systems and is explored in detail in the subsequent section.

5. Substrate–Nutrient Interactions in Hydroponic Systems

The performance of hydroponic systems is fundamentally governed by the interactions between growing substrates and nutrient composition within the root zone. While substrates and nutrient solutions have often been studied as independent factors, increasing evidence indicates that their combined effects play a more critical role in determining plant growth, nutrient uptake efficiency, and yield outcomes. In hydroponic pepper production, including Super Habanero pepper, these interactions influence root zone conditions, regulate nutrient availability, and ultimately shape plant physiological responses (Serralta-Interian et al., 2020). Understanding substrate–nutrient interactions requires an integrated perspective that considers physical, chemical, and biological processes occurring within the root environment. These interactions determine how nutrients are retained, transformed, and absorbed by plant roots, making them central to optimising hydroponic production systems.

5.1 Concept of Substrate–Nutrient Interactions

Substrate–nutrient interactions refer to the dynamic processes through which the physical and chemical properties of the growing medium influence the behaviour, availability, and uptake of nutrients supplied through hydroponic solutions (Silber and Bar-Tal, 2019). These interactions occur at the root–substrate interface, where plant roots, nutrient solution, and substrate materials come into continuous contact.

In hydroponic systems, the root zone environment is highly sensitive to changes in substrate structure and nutrient composition. Substrates with different porosity, surface area, and chemical properties can alter the distribution and movement of nutrient ions, thereby affecting their accessibility to plant roots. At the same time, nutrient solutions can modify substrate characteristics through processes such as salt accumulation, pH shifts, and ion exchange. The interaction between substrates and nutrients is therefore bidirectional. Substrates influence nutrient behaviour, while nutrient solutions alter substrate conditions (Xu et al., 2018). This dynamic relationship plays a critical role in determining nutrient use efficiency and plant performance. In practical terms, optimal hydroponic production requires the selection of substrates and nutrient formulations that complement each other, ensuring a stable and balanced root zone environment.

5.2 Influence of Substrates on Nutrient Availability

Substrates significantly influence nutrient availability through their capacity to retain, release, or restrict the movement of nutrient ions within the root zone. This influence is largely determined by substrate properties such as porosity, cation exchange capacity, and water holding capacity. Substrates with high water retention capacity, such as coco peat, can hold nutrient solutions for longer periods, providing a more consistent supply of nutrients to plant roots (Atzori et al., 2021). However, excessive water retention may reduce oxygen availability and slow down nutrient uptake if not properly managed. On the other hand, highly porous substrates such as perlite enhance aeration but may allow rapid drainage, leading to nutrient leaching and reduced nutrient use efficiency.

Cation exchange capacity plays a critical role in nutrient retention. Substrates with higher cation exchange capacity can adsorb positively charged ions such as potassium, calcium, and magnesium, releasing them gradually as plant roots absorb nutrients from the solution. This buffering effect stabilizes nutrient supply and reduces fluctuations in nutrient concentration (Ngo et al., 2023). Organic substrates, which are commonly used in Nigeria due to their availability and cost-effectiveness, may also influence nutrient availability through decomposition processes. As these materials break down, they can immobilise certain nutrients, particularly nitrogen, making them temporarily unavailable to plants. At the same time, decomposition may release other nutrients, contributing to variability in nutrient supply. Substrate particle size and structure also affect nutrient distribution within the root zone. Fine particles may retain more water and nutrients but reduce aeration, while coarse particles improve aeration but may limit nutrient retention. The balance between these factors is essential for maintaining optimal root zone conditions (Ma et al., 2018).

5.3 Influence of Nutrients on Substrate Properties

While substrates affect nutrient behaviour, nutrient solutions can also modify the physical and chemical properties of substrates over time. One of the most significant effects is the alteration of pH within the root zone. Nutrient uptake by plants can lead to the release of hydrogen or hydroxyl ions, causing shifts in substrate pH that may influence nutrient solubility and microbial activity. Electrical conductivity of the substrate is also affected by nutrient composition. Continuous application of nutrient solutions can lead to salt accumulation within the substrate, particularly in systems with limited drainage (Othman et al., 2019). High salt concentrations can create osmotic stress, reducing the ability of plant roots to absorb water and nutrients effectively.

Inorganic substrates such as rockwool are generally less reactive to changes in nutrient composition, maintaining stable physical properties over time. In contrast, organic substrates may undergo structural changes as a result of prolonged exposure to nutrient solutions. These changes can affect porosity, water retention, and aeration, thereby influencing overall plant performance. Nutrient composition can also influence microbial activity within the substrate, particularly in organic media (Xu et al., 2018). The presence of certain nutrients can stimulate microbial growth, which may enhance nutrient cycling but also introduce variability in nutrient availability. In tropical environments such as Nigeria, where high temperatures favour microbial activity, these effects can be more pronounced.

5.4 Interaction Effects on Plant Growth and Yield

The combined effects of substrates and nutrient composition on plant growth and yield are often more significant than their individual contributions. These interactions can be either synergistic or antagonistic, depending on how well the substrate and nutrient regime complement each other (Sarsan et al., 2022). Synergistic interactions occur when substrate properties enhance the effectiveness of nutrient solutions. For example, a substrate with balanced water retention and aeration can improve nutrient uptake efficiency, leading to increased growth and higher yields. In such cases, the substrate and nutrient solution work together to create optimal root zone conditions. Antagonistic interactions, on the other hand, arise when substrate characteristics limit nutrient availability or uptake. For instance, a substrate with poor drainage may lead to waterlogging, reducing oxygen availability and impairing nutrient absorption. Similarly, excessive nutrient concentrations in a substrate with low buffering capacity may result in toxicity or osmotic stress.

In hydroponic pepper production, these interactions influence key growth parameters such as root development, leaf area, flowering, fruit set, and yield. For the Super Habanero pepper, optimal substrate–nutrient combinations are essential for achieving high fruit yield and maintaining desirable quality traits such as pungency, colour, and shelf life (Islam et al., 2023). In Nigerian where locally available substrates are often used in combination with variable nutrient formulations, understanding these interactions is particularly important. Variability in substrate quality and nutrient supply can lead to inconsistent production outcomes, highlighting the need for integrated management strategies that consider both factors simultaneously.

5.5 Implications for Hydroponic System Optimisation

The understanding of substrate–nutrient interactions has important implications for the design and management of hydroponic systems. Rather than selecting substrates and nutrient solutions independently, producers must adopt an integrated approach that considers their combined effects on root zone conditions. Optimisation strategies may include matching substrates with appropriate irrigation schedules, adjusting nutrient concentrations based on substrate properties, and monitoring root zone parameters such as pH and electrical conductivity. In addition, the use of locally available substrates in Nigeria requires proper processing and standardisation to ensure consistent performance.

Advances in hydroponic technology, including sensor-based monitoring and automated nutrient delivery systems, offer opportunities to better manage substrate–nutrient interactions. These technologies can help maintain optimal conditions within the root zone, improving nutrient use efficiency and enhancing crop productivity. Ultimately, the successful cultivation of Super Habanero pepper in hydroponic systems depends on the ability to effectively manage the complex interactions between substrates and nutrient composition. A deeper understanding of these interactions will support the development of more efficient, sustainable, and regionally adapted hydroponic production systems.

5.6 Evidence from Previous Studies on Hydroponic Pepper Production

Hydroponic pepper production is highly responsive to both nutrient management and substrate selection (Table 1). Empirical evidence from previous studies on hydroponically grown peppers has demonstrated that plant growth, yield, and fruit quality are strongly influenced by nutrient solution composition, substrate type, and their interactions. Although crop-specific studies on Super Habanero pepper remain limited, findings from both Habanero and other pepper species provide a robust basis for understanding hydroponic production responses. Studies focusing on Habanero pepper have shown that nutrient solution formulation significantly affects plant development and productivity. Meneses-Lazo et al. (2020) reported that variations in nutrient solution composition influence phenological development and fruit quality in hydroponically grown Habanero pepper. Similarly, López-Gómez et al. (2017) found that different nutritional regimes significantly affect yield and fruit quality traits such as fruit size, weight, and pungency. These findings confirm that nutrient balance is a key determinant of both quantitative and qualitative yield outcomes in hydroponic Habanero production.

Table 1. Summary of selected studies on hydroponic pepper production systems

Crop Type	System/Condition	Key Factor Studied	Key Finding	Author(s)
Habanero pepper	Hydroponic system	Nutrient solution composition	Nutrient formulation strongly affects development and quality	Meneses-Lazo et al. (2020)
Habanero pepper	Soilless system	Nutrient solution × substrate interaction	Substrate modifies nutrient response	Bustamante et al. (2023)
Habanero pepper	Hydroponic system	Nutritional regime	Nutrient regimes influence yield and pungency	López-Gómez et al. (2017)
Bell pepper	Closed hydroponic system	Nutrient solution concentration	Nutrient concentration affects efficiency and yield	Giuffrida and Leonardi (2012)
Bell pepper	Low-tech hydroponic system	System type and cultivation method	Hydroponics viable even in low-tech systems	Schnitzler et al. (2001)
Bell pepper	Protected environment	K^+/Ca^{2+} ratio under salinity	Ionic balance critical under stress conditions	Silva et al. (2020)

The role of substrate and soilless growing media has also been emphasised in recent studies. Bustamante et al. (2023) demonstrated that Habanero pepper grown in different soilless media exhibited variable growth and yield responses depending on the nutrient solution applied, highlighting the importance of substrate–nutrient interaction in hydroponic systems. This interaction is critical because substrates influence water retention, aeration, and nutrient availability in the root zone. Evidence from related *Capsicum annuum* studies further strengthens these findings. Giuffrida and Leonardi (2012) reported that nutrient solution concentration significantly affects yield, fruit quality, and nutrient use efficiency in pepper grown in closed hydroponic systems. In addition, Schnitzler et al. (2001) demonstrated that low-tech hydroponic systems can successfully support bell pepper production, reinforcing the adaptability of hydroponic systems across different technological levels. Silva et al. (2020) further showed that fertigation strategies combined with balanced potassium to calcium ratios under salinity stress conditions significantly influence bell pepper growth and yield, highlighting the sensitivity of pepper crops to nutrient balance and ionic composition. These findings suggest that differences observed across studies are not solely due to nutrient composition but also reflect the modifying role of substrate properties on nutrient availability and uptake.

6. Current Advances in Hydroponic Pepper Production

Recent developments in hydroponic technology have significantly improved the efficiency, sustainability, and productivity of crop production systems. In pepper cultivation, including Super Habanero pepper, these advances have focused on improving substrate performance, optimising nutrient delivery, and integrating innovative technologies to enhance overall system management. The increasing emphasis on precision agriculture and controlled environment systems has further driven research into methods that maximise yield while minimising resource use and environmental impact.

In Nigeria and other developing regions, these advances present both opportunities and challenges. While modern hydroponic technologies offer the potential to improve food production and agribusiness development, their adoption is often constrained by cost, technical expertise, and infrastructure limitations. Nevertheless, the adaptation of these innovations to local conditions is gradually shaping the future of hydroponic pepper production.

6.1 Innovative Substrate Technologies

One of the major areas of advancement in hydroponics is the development of improved and sustainable growing substrates. Traditional substrates such as coco peat, perlite, and rockwool are being complemented or replaced by alternative materials designed to enhance water retention, aeration, and nutrient buffering capacity (Blok et al., 2024). Biochar has gained considerable attention as a promising substrate component due to its high surface area, porosity, and ability to retain nutrients (Ayaz et al., 2021). It also contributes to improved microbial activity within the root zone, which can enhance nutrient cycling and plant growth. Similarly, composite substrates that combine organic and inorganic materials are being developed to achieve an optimal balance between water retention and aeration.

Recyclable and biodegradable substrates are also becoming increasingly important in response to environmental concerns associated with synthetic materials such as rockwool (Blok et al., 2024). The use of agricultural residues, including rice husk and coconut fibre, aligns with sustainable production practices and is particularly relevant in Nigeria, where such materials are readily available (Anosike-Francis et al., 2025). However, standardisation of these materials remains a challenge due to variability in quality and composition. Advances in substrate processing techniques, including sterilisation and particle size optimisation, have further improved substrate performance by reducing pathogen risks and enhancing uniformity.

6.2 Advances in Nutrient Management

Nutrient management in hydroponic systems has evolved from simple nutrient solution preparation to highly precise and controlled delivery systems. Modern approaches emphasise the optimisation of nutrient composition based on plant growth stage, environmental conditions, and system design. Precision nutrient management involves adjusting nutrient concentrations and ratios in real time to match plant requirements (Gorai et al., 2021). This approach reduces nutrient wastage and improves uptake efficiency. The use of pre-formulated nutrient solutions tailored for specific crops, including peppers, has also improved consistency in hydroponic production.

Another significant advancement is the integration of sensors and monitoring systems to track parameters such as pH, electrical conductivity, temperature, and dissolved oxygen within the nutrient solution (Abdulhussain et al., 2025). These technologies enable continuous monitoring and rapid adjustment of nutrient conditions, thereby maintaining optimal root zone environments. In Nigeria, while the adoption of advanced nutrient management systems is still limited, there is increasing interest in low-cost monitoring tools and simplified nutrient formulations that can be adapted to local conditions. Capacity building and training are essential for enabling producers to effectively implement these technologies.

6.3 Integrated Optimisation Strategies

A key trend in hydroponic research is the integration of multiple factors to achieve optimal system performance. Rather than focusing on individual components such as substrates or nutrients, modern approaches emphasise the need for coordinated management of all elements within the production system. Integrated optimisation involves matching substrate properties with appropriate nutrient regimes, irrigation schedules, and environmental conditions (Zhao et al., 2024). For example, substrates with high water retention may require less frequent irrigation but careful monitoring of oxygen availability, while highly porous substrates may require more frequent nutrient application to prevent nutrient loss.

Controlled environment agriculture, including greenhouse and indoor farming systems, has further enhanced the ability to regulate environmental factors such as temperature, humidity, and light (Ragaveena et al., 2021). These systems allow for precise control of plant growth conditions, improving yield and quality while reducing the impact of external environmental variability. The use of automation and data-driven decision-making tools is also becoming more prevalent. These technologies enable producers to optimise resource use, reduce labour requirements, and improve overall system efficiency.

6.4 Application to Super Habanero Pepper

Although specific studies on Super Habanero pepper in hydroponic systems are relatively limited, insights can be drawn from research on related *Capsicum* species. These studies demonstrate that optimised combinations of substrates and nutrient regimes can significantly enhance growth, yield, and fruit quality. Hydroponic cultivation of peppers has been associated with increased fruit uniformity, improved colour development, and enhanced pungency levels, which are important quality attributes for Super Habanero pepper (Bhattarai et al., 2025). The ability to control nutrient supply during critical growth stages allows for targeted enhancement of these characteristics.

In Nigeria, the application of advanced hydroponic techniques to Super Habanero pepper production offers significant potential for expanding commercial cultivation and meeting both local and export market demands. However, successful implementation will require adaptation of technologies to local conditions, including the use of affordable substrates and simplified nutrient management systems. The integration of innovative substrates, precise nutrient management, and controlled environment systems represents a promising pathway for improving the productivity and sustainability of hydroponic pepper production in Nigeria.

7. Challenges and Future Research Directions in Hydroponic Pepper Production

Despite the growing interest in hydroponic systems for pepper cultivation, several challenges continue to limit their widespread adoption and optimal performance, particularly in developing regions such as Nigeria. Addressing these constraints requires a clear understanding of existing knowledge gaps and the development of targeted research and innovation strategies. One of the major challenges in hydroponic pepper production is the limited understanding of substrate–nutrient interactions under different environmental and management conditions (Tuxun et al., 2025). While numerous studies have examined substrates and nutrient composition independently, there is a lack of comprehensive experimental and modelling approaches that evaluate their combined effects. Future research should therefore focus on integrated studies that systematically investigate how different substrate types interact with specific nutrient regimes to influence plant growth, yield, and resource use efficiency. Another significant limitation is the lack of standardised protocols for substrate selection and nutrient formulation. Variability in substrate properties, particularly for locally sourced materials such as rice husk and sawdust in Nigeria, can lead to inconsistent production outcomes. This inconsistency is further compounded by variations in nutrient solution preparation and management practices (Pascual et al., 2018). To address this, future studies should aim to develop standardised guidelines and locally adapted best practices for substrate processing, characterisation, and nutrient formulation tailored to specific crops such as Super Habanero pepper.

Economic and technical constraints also pose major challenges to the adoption of hydroponic systems (Sousa et al., 2024). High initial investment costs, limited access to quality inputs, and inadequate technical expertise restrict the scalability of hydroponic production in many parts of Nigeria. Research efforts should therefore prioritise the development of cost-effective hydroponic technologies, including the use of affordable and locally available substrates, simplified nutrient management systems, and low-cost monitoring tools that can be easily adopted by small and medium-scale producers. Environmental factors, particularly in tropical regions, present additional challenges in maintaining stable hydroponic conditions (Kailashkumar et al., 2023). High temperatures can affect nutrient solution stability, increase evapotranspiration rates, and alter root zone dynamics, thereby impacting plant growth and productivity. Future research should explore adaptive strategies for managing hydroponic systems under tropical conditions, including improved system design, temperature regulation techniques, and climate-resilient production models.

Another important knowledge gap relates to the limited availability of crop-specific data for the Super Habanero pepper. Most existing studies focus on general *Capsicum* species, with relatively few addressing the unique growth characteristics and nutrient requirements of this specific cultivar. Future research should therefore include targeted studies on Super Habanero pepper to establish optimised substrate–nutrient combinations and production protocols that enhance yield and fruit quality. There is also a need to explore the role of microbial interactions within hydroponic substrates, particularly in organic media. Beneficial microorganisms can enhance nutrient availability and plant health, but their interactions with substrates and nutrient solutions remain poorly understood. Advances in this area could lead to the development of biologically enhanced hydroponic systems that improve sustainability and productivity. Technological advancements such as automation, sensor-based monitoring, and data-driven decision-making offer promising solutions for improving hydroponic system management (Reza et al., 2025). However, their adoption in Nigeria is still limited due to cost and technical barriers. Future efforts should focus on adapting these technologies to local contexts, developing user-friendly systems, and promoting capacity building through training and education.

8. Conclusion

This review demonstrates that substrate–nutrient interactions are central to the successful hydroponic production of Super Habanero pepper, influencing nutrient availability, root zone conditions, and overall plant performance. Rather than acting independently, substrates and nutrient solutions interact dynamically to regulate water retention, aeration, ion exchange, and nutrient uptake efficiency. These interactions ultimately determine key production outcomes, including growth rate, yield, fruit quality, and pungency. Evidence from global studies on *Capsicum* species confirms that optimised combinations of substrates and nutrient regimes can significantly enhance productivity in hydroponic systems. Substrates such as coco peat, perlite, and their blends provide favourable physical conditions for root development, while balanced nutrient formulations ensure the adequate supply of essential elements required for physiological processes. However, the effectiveness of these components depends on their compatibility and proper management within the root zone environment.

In Nigeria, hydroponic production of Super Habanero pepper presents a promising opportunity for improving food security, supporting urban agriculture, and expanding agribusiness potential. The use of locally available substrates such as rice husk and sawdust offers cost advantages but requires standardisation to ensure consistent performance. Challenges related to technical expertise, input availability, and environmental conditions must also be addressed to facilitate wider adoption. Future research should focus on developing locally adapted substrate–nutrient combinations, establishing standardised production protocols, and integrating cost-effective technologies suited to tropical conditions. By adopting an integrated approach to substrate and nutrient management, hydroponic systems can be optimised to achieve sustainable and high-quality pepper production in Nigeria and similar developing regions.

Disclaimer (Artificial Intelligence)

The authors hereby declare that limited generative AI assistance was used solely for language editing and manuscript improvement.

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Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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