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The effect of organic and chemical fertilization on the growth and yield of cucumbers (*Cucumis sativus* L.) under protected cultivation conditions: Comprehensive review.

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Abstract:

The cultivation of cucumbers (Cucumis sativus L.) in protected greenhouses requires careful nutrient management to maintain rapid plant growth, high fruiting rates, and continuous harvesting. This review compiles evidence on organic and chemical fertilization strategies and their effects on growth, yield, fruit quality, soil health, and sustainability. Chemical fertilizers (especially N–P–K via top dressing) promote early activity, leaf area, and marketable yield through readily available nutrients and controllable doses. However, exclusive reliance on them can exacerbate soil salinity, nutrient imbalance, and environmental pollution, especially under intensive year-round production. Organic amendments (compost, manure, digestate, biochar, and plant extracts) improve cation exchange capacity, water retention, and microbial activity, often leading to improved fruit quality (dry matter, firmness, soluble solids, vitamin C) and reduced physiological disorders. Crop responses to organic fertilizers alone vary, reflecting the quality of amendments, mineralization rates, and temperature-dependent decomposition common in protected systems. In all studies, integrated nutrient management — combining basic organic amendments and soluble mineral fertilization — provides the most reliable results: higher nutrient use efficiency, stable yields, improved storage life, and partial (20–50%) replacement of synthetic nitrogen without affecting yield. Economic analyses generally favor integrated programs when organic inputs are locally available and fertigation is optimized. Future priorities include standardizing organic input characterization, modeling N mineralization under protected microclimates, and long-term trials that jointly track yield, quality, and soil biological indicators to define fertilizer substitution thresholds for resilient cucumber production.

Keywords: *Cucumis sativus* L., protected cultivation, fertigation, chemical fertilizers, integrated nutrients.

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1. Introduction

Fertilization represents a critical management input for crop systems, essential for providing important crop nutrients in a suitable form and quantity, and applied at the proper time and place. It plays a fundamental role in agricultural productivity by addressing deficiencies of nitrogen (N), phosphorus (P), potassium (K), and other microelements,

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thereby satisfying crop requirements and compensating for losses due to leaching, surface runoff, volatilization, erosion, and immobilization (1). Crop yields without fertilization are often insufficient to meet the needs of a large and increasing human population. In protected environments, fertilizers not only contribute to the provision of essential plant nutrients but also influence the microclimate by affecting soil heat and water conductivity, especially in autumn–winter–spring conditions when fertilizer responsiveness describes the additional yield attained with fertilization compared to unfertilized conditions (2). Both organic and chemical fertilization play pivotal roles in enhancing cucumber growth and productivity; however, a complete and satisfactory evaluation of their respective effects has yet to be established (3).

2. Overview of Cucumber Cultivation

Cucumber (Cucumis sativus), a widely cultivated creeping vine in the Cucurbitaceae family, is one of the most important vegetable crops (4). It is grown under open-field and protected cultivation. Open-field cultivation is highly affected by water stress, irregular rainfall, and other climatic elements, while protected cultivation techniques protect crops from fluctuating and extreme weather conditions (5). Protected cultivation enhances yield and product quality (6). Fertilizers are essential for providing balanced essential plant nutrients throughout the crop production cycle (7). Cucumber, being a fast-growing season crop with a high nutrient requirement, particularly for nitrogen (N) and potassium (K), is influenced significantly by the fertilizer type and quantity applied (8). Organic and inorganic fertilizers make a vital contribution to total fertilizer consumption, with organic fertilizers raising cucumber production by enhancing major soil nutrients (9).

3. Protected Cultivation: Concepts and Benefits

Protected cultivation enables the realization of higher yields and improved quality of various sheltered crops. These crops occur and adapt in high determination and maintain strong responsiveness to fertilizers and other cultural practices (10). Protected cultivation of vegetables is a specialised system of vegetable production where all the growth conditions, including temperature, relative humidity, light, carbon dioxide levels, and other important factors that influence plant growth, development, and productivity, are kept under strict control (11).

4. Fertilization in Agriculture

Fertilization is defined as the supplementation of soil fertility on the basis of the field crop requirement. It regulates plant growth and productivity and increases the quantity of desired product to meet the demands of a growing population (12). At the initial stage of plant growth, a continuous supply of soil nutrients through fertilizers is required for proper growth and development, which influences the quality and quantity of agricultural products. Fertilizer not only compensates for the loss of nutrients from the soil but also maintains soil nutrient balance and promotes the activities of microorganisms in the soil (13). Different plants have different nutrient requirements depending on soil type and fertility status. Fertilizer requirement in a plant not only depends on soil type and fertility but also on the plant growth environment, such as an open field or a protected environment. The protection of plants under a tunnel, glass greenhouse, shade house, and plastic house is considered protected cultivation (14). Plants grow more quickly under a protected environment due to optimum water and nutrient availability, and also have higher physiological activities such as photosynthesis and transpiration. Therefore, plants have an ample supply of nutrients under a protected environment and use fertilizer more effectively than in an open field. Thus, applying fertilizer at the right quantity plays a vital role in increasing crop productivity (15). Among different crops cultivated under protected conditions, cucumber is a major fruit widely cultivated because of its quick maturing habit and high nutritional value. Cucumber requires large

quantities of nutrients, especially nitrogen, phosphorus, and potassium, for quick growth and high yield (16).

5. Types of Fertilizers

Fertilizers are organic or inorganic, natural or synthetic substances that provide the plant with the nutrients needed to grow and increase its production during the different stages of growth (17).

5.1 Organic Fertilizers

Organic fertilizers provide good, balanced nutrition to plants and release nutrients slowly over a long period. Organic fertilizers contain many essential nutrients for crops. Crops get various macro and micronutrients to the soil through organic matter. Augmentation of microbial activity in the soil makes the nutrients available to plants. Organic fertilizers are obtained from animal and plant remains such as farmyard manure, compost, vermin compost, trangamree, nitrogen-fixing bacteria, and green manure (18).

5.2 Chemical Fertilizers

Chemical Fertilizers are man-made fertilizers with a high concentration of elements such as N, P, and K, and are normally in water-soluble form (19).

5.1. Organic Fertilizers

Organic fertilizers consist of animal manure and plant materials that supply plant nutrients. Generally, organic fertilizers are a relatively poor source of mineral nutrients; however, their use in agricultural systems can benefit crop growth and productivity by influencing the physical, chemical, and biological characteristics of soil (20). Experimental results showed that plant nutrients are released more slowly from organic fertilizers than from chemical fertilizers; hence, their use reduces the risks of nutrient losses and leaching at early crop growth stages. Consequently, organic fertilizers provide balanced nutrition as well as support and enhance nutrient use efficiency (21).

5.2. Chemical Fertilizers

Chemical fertilizers serve as synthetic sources of essential plant nutrients, delivering nitrogen (N), phosphorus (P), and potassium (K) in rapidly available forms. Inspired by principles of nutrient supplementation and recovery, they consist of biologically processed chemical compounds that dissolve swiftly upon application, making nutrients immediately accessible to plants. As a consequence of their quick solubility, chemical fertilizers provide an expeditious nourishment regime for crops. In contrast to organic types, chemical fertilizers release nutrients almost instantly, whereas organic fertilizers release nutrients through a slow decomposition process. For a further exposition on the conceptual framework of nutrient supplementation in crop production, the reader is referred to the title “Fertilization in Agriculture.” (22)

6. Impact of Organic Fertilization on Cucumber

Organic fertilization can improve the growth and yield of the cucumber. Organic fertilizers may provide extensive crop nutrition when mineral nutrients from non-renewable sources become limited (23). The use of organic fertilizers for crop production could be a cost-saving and environmentally friendly practice. It is therefore necessary to test the feasibility of organic fertilization mechanisms for the development of sustainable cultivation strategies in the protected-cultivation system (24).

6.1. Nutritional Benefits

The application of organic fertilizers to cucumber improves the availability of macro- and micronutrients, increasing nutrient uptake by crops and encouraging early and vigorous growth (3). This practice can solve many soil–soil-fertilization problems and improve the nutrient content of crops. Organic materials contain small amounts of easily available plant nutrients, and most nutrients are present in an insoluble form (18). As organic manures decompose, they release nutrients in a

quantity and balance that support plant growth, and, in the long term, they improve the physical and biological condition of the soil. These improvements in soil condition increase microbially mediated nutrient transformations and enhance nutrient uptake and crop growth. Organic amendments applied to cucumber plants dose-dependently increased seed germination and seedling growth (25).

6.2. Soil Health Improvement

Enhancing soil quality by establishing a nutrient-rich and well-textured environment is fundamental for achieving higher crop productivity (3). Organic fertilizers improve soil structure, conserve moisture, enhance water-holding capacity, and stimulate microbial activity, which in turn reduces soil pathogens. Such fertilizers are especially advantageous for small-scale or low-input farming systems, effectively improving soil fertility, mitigating the adverse effects of chemical fertilizers, and reducing costs, thereby increasing productivity (20). Frequent application of chemical fertilizers can lead to soil structure deterioration, nutrient imbalances, and hindered nutrient absorption (19).

Organic fertilizers also reduce compaction, improve porosity and drainage, enhance air circulation, and prevent erosion and nutrient leaching (26). The chemical composition and nutrient release rates of organic fertilizers differ substantially from those of chemical fertilizers. Organic manures support microbial activity and supply nutrients over extended periods compared to inorganic alternatives (20). The use of organic fertilizers promotes the accumulation of soil organic matter and activates soil nutrients, further improving soil structure. Soil health decline and fertility loss can be counteracted through the judicious application of balanced fertilization systems. When combined with organic amendments, these systems maintain a healthy soil ecosystem and support sustainable agricultural development (27).

6.3. Environmental Considerations

Long-term application of high levels of chemical fertilizer causes soil acidification and hardening and reduces soil microbial diversity, as well as increasing the disappearance of soil arbuscular mycorrhizal fungi (AMF) (expressed as percentage reduction) (1). Excessive fertilization (over-application) decreases soil pH and reduces soil PLFAs content as well as the abundance of AMF and fungi in the rhizosphere, while increasing bacterial proportions; yields under a balanced fertilization regime exceed those under the excessive regimen (28). The inevitably decreased beneficial microbial populations and rhizosphere metabolites associated with over-fertilization are responsible for declining soil health and yield. Alternatively, low-dose organic fertilizer increases soil organic acids and hydrocarbons, promoting fruit yield and quality while lowering production costs relative to chemical fertilizers (3). The positive outcomes result from balanced nutrition, enriched microbial populations, improved soil structure, and synergistic effects with biofertilizers; microbial growth is enhanced by the protection and stimulation provided by organic amendments (29).

7. Impact of Chemical Fertilization on Cucumber

Although organic fertilization could sustain normal growth and even yield enhancement, chemical fertilization showed varying impacts on cucumber under protected cultivation (1). Crop growth and production of cucumber benefit considerably from protection structures under conditions of excessive chemical inputs. Fertilization significantly increases chlorophyll contents in leaves, and the chlorophyll a under N2P2K2 treatment and the chlorophyll b under the N2P2K2 and N3P3K3 treatments are significantly higher than those under other treatments. In addition, dry weights under fertilization treatments are significantly higher than under no fertilization. Crop productivity and health

depend on balanced nutrient supply (30). Combinations of inorganic, organic, and biofertilizers improve the earliness and productivity of cucumber by increasing fruit count, weight, length, cavity, volume, and diameter due to balanced nutrition and better nutrient uptake (31).

7.1. Immediate Growth Responses

Chemical fertilizers provide a readily available nutrient supply to cucumber plants and promote immediate growth response, emphasizing rapid nutrient uptake and swift development evident in the initial growth stages (3). Cucumber plants respond to chemical fertilization with increased leaf area and enhanced biomass accumulation. Such fertilizers ensure a balanced nutrient availability, supporting a quick increase in vegetative growth parameters. However, the long-term reliance on chemical fertilizers bears negative consequences, such as pH degradation of soils, solubility enhancement of toxic metals, acceleration of soil acidification, inhibition of nitrification activities, and supply-demand imbalances that contribute to lower long-term productivity and sustainability. Additionally, excessive use leads to health and environmental concerns, including soil salinization, groundwater pollution, and eutrophication. In contrast, organic fertilization sustains soil nutrient levels, ameliorates soil quality, and supports higher long-term availability, thereby favoring vegetative growth through improved soil properties (16). Organic fertilizers enhance soil structure and provide improved water-holding capacity, which in turn facilitates nutrient absorption, augments microbial diversity, and elevates enzyme activity. These characteristics collectively foster a conducive environment for prolonged vegetative development, culminating in increased leaf expansion and further biomass accumulation over time (32). Under protected cultivation, the nutrient uptake by cucumber plants is allegedly higher than in open fields, and consequently, both organic and chemical fertilization can affect the growth and yield of cucumber (33).

7.2. Long-term Soil Effects

Organic fertilizers are derived from farm and domestic waste materials and contain a wide variety of nutrients in addition to primary, secondary, and micronutrients. They generally have a slower release mechanism than chemical fertilizers, exhibiting improved nutrient release efficiency, storage capacity, and less chance for leaching (34). As the organic fertilizer undergoes decomposition, it releases nutrients in forms available for plant growth. These nutrients are converted into inorganic compounds capable of being taken up by plant roots. This form of nutrient supply ensures a consistent and balanced release of nutrients that remain available throughout the growing period, potentially stunting growth and yield if depleted prematurely. Additionally, organic fertilizers improve soil texture, increase microbial activity, enhance water and nutrient exchange capacities, and reduce soil erosion and evaporation, collectively promoting sustainable crop production (35).

7.3. Health and Safety Concerns

Chemical fertilizers contain readily soluble mineral constituents with immediate availability to plants. However, extensive chemical fertilization can negatively influence soil microflora diversity and activity, resulting in impaired soil properties, reduced natural soil productivity, and lowered crop quality. Additionally, long-term use of chemical fertilizers alongside intensive cropping and improper irrigation leads to mineral imbalances, nutrient accumulation, soil acidity changes, and soil texture modifications in agricultural land (36). The accumulation of certain elements may exert toxic effects on plants and soil-dwelling organisms, such as earthworms, bees, and butterflies, thereby disrupting the natural equilibrium of agro-ecological systems. Moreover, residues of synthetic fertilizers that persist in food materials can have toxicological implications for human health (37).

Given the importance of soil fertility in agricultural development, the fertilizer industry, encompassing both organic and chemical fertilizers, is pivotal to

any country's agro-based economy (38). The growing negative impact of chemical fertilizers on natural ecological systems and the environment underscores the urgent need to explore and develop novel organic fertilization approaches. The subsequent sections undertake a critical comparative evaluation of the influence of organic and chemical fertilizers on cucumber growth and yield under protected cultivation, thereby informing future applications and research directions.

8. Comparative Analysis of Organic and Chemical Fertilizers

The cultivation of cucumber (*Cucumis sativus* L.) in greenhouses and tunnels has gained popularity recently due to consumer demand for high-quality vegetables with minimal pesticide residues (3). Fertilization plays a critical role in enhancing cucumber growth and yield under protected cultivation. Both organic and chemical fertilizers have been widely verified to improve crop production through the amendment of soil fertility. Organic fertilizers, comprising various organic materials such as farmyard manure, compost, and biofertilizers, are rich in essential nutrients that can directly or indirectly promote crop growth. Application of organic fertilizers can increase nutrient availability, improve soil physical, chemical, and biological properties, and induce beneficial environmental effects (39). Chemical fertilizers, on the other hand, provide readily bioavailable nutrients to crops and tend to support quick plant growth and higher biomass. However, excessive and continuous use of chemical fertilizers can lead to nutrient imbalances, soil acidification, contamination from hazardous chemicals, and environmental pollution—all of which can seriously threaten agricultural sustainability (40).

Previous studies have compared the effects of organic and chemical fertilization on cucumber growth and yield under protected cultivation with conflicting results. Some research reports that organic fertilizer leads to better plant development and increased productivity, while other work highlights the beneficial growth responses and immediate nutrient supply associated with chemical fertilizers (41). Fertilizer market prices also influence growers' adoption choices. Therefore, a rigorous evaluation of the impacts of organic versus chemical fertilization on cucumber growth and productivity under greenhouse and tunnel conditions is necessary to provide guidance for growers, operators, and resource managers (42). The present study addresses this need by comparing the fertilization performances of organic and chemical inputs on cucumber cultivated under protected environments.

8.1. Yield Outcomes

Cucumber (*Cucumis sativus* L.) ranks among the most extensively cultivated vegetable crops worldwide, particularly in tropical regions where it serves both consumption and export purposes 3. Horticultural production under protected environments, such as greenhouses, has markedly increased in recent decades owing to favorable microclimates that promote enhanced yields (6). In crop production, fertilization constitutes one of the primary inputs, yet excessive or irrational application of chemical fertilizers can degrade soil physico-chemical properties and reduce microbial biodiversity, thereby diminishing yield. Consequently, there is a vital research imperative to investigate how fertilization regimes—organic, chemical, or a combination of both—affect the growth and yield of cucumbers grown under protected cultivation (43). Comparative studies examining the influence of these fertilization strategies offer crucial insights for optimizing crop productivity.

8.2. Cost-Effectiveness

The comparison of organic and chemical fertilization underlines a significant disparity in cost-effectiveness, with organic options delivering equal yields at considerably lower expenses. Faced with the environmental footprint of synthetic fertilizers, many small to medium-scale growers circumvent the

costs and contamination risks of chemical alternatives by opting for on-site composting or collecting animal manure. Despite the higher expense often attributed to organic fertilizers, their local production potential renders them an economically viable choice for resource-constrained farmers (44). Integrating liquidity conditioners, such as molasses, enhances the release of essential nutrients like Calcium, Magnesium, and Potassium from organic amendments. However, the imprecision in dosage control, coupled with undetermined application thresholds relative to crop tolerance, necessitates further refinement to optimize financial efficiency and agronomic performance (3,45).

8.3. Sustainability Aspects

The issues of environmental pollution and undesirable agricultural effects arising from chemical fertilizer use have led to a growing need for sustainable and environmentally friendly agricultural practices (3). Carbon footprints are a crucial factor in this context, as low carbon emissions are necessary to reduce global warming. Studies have observed that compared to chemical fertilizers, crop production with organic fertilizers tends to promote soil health and reduce carbon footprint (46). The findings suggest that long-term fertilization is pivotal in determining the carbon footprint of cucumber cultivation, and replacing chemical fertilizers with organic alternatives could be an effective means of lowering global warming potential within the agricultural sector (47).

9. Case Studies

Real-world applications highlight the practical implications of the comparative effects of organic and chemical fertilizers (3). Case studies illustrate the advantages and challenges associated with each approach.

9.1 Successful Organic Fertilizer Application

An experiment conducted in Nigeria examined the influence of organic, inorganic, and biofertilizers on cucumber under a microirrigation-plastic mulch regime. Results demonstrated that combinations of inorganic, organic, and biofertilizers promoted earliness and enhanced productivity. Increased fruit number and weight per plant ultimately translated into higher yield per hectare. Growth parameters such as fruit length, cavity, volume, and diameter also improved, attributed to balanced nutrition, enhanced nutrient uptake, and augmented carbohydrate synthesis (48). Biofertilizers such as Azotobacter, applied alone or alongside organic fertilizer, further elevated quantitative and qualitative traits of summer squash—a close relative of cucumber. The interaction of bio and organic fertilizers yielded optimal performance regarding yield and quality. These effects stemmed from the release of growth-promoting compounds like cytokinins and Indole Acetic Acid (IAA), as well as siderophores that increase iron availability for various biophysical and biochemical processes (49). Additionally, Azotobacter indirectly improved soil structure through excreted polysaccharides, which help maintain soil particle cohesion (50). The findings underscore the synergistic potential of combining fertilizers with biofertilizers to enhance soil status and boost crop yields.

9.1. Successful Organic Practices

In the northern regions of Nigeria, many farmers who lack adequate technical knowledge of the recommended nutrient requirements for cucumber crops apply fertilizer without a clear understanding of the appropriate rates. Generally, farmers tend to invest more in fertilizers than is biologically necessary, and nutrient quantities are often inadequately balanced, leading to negative effects on crop growth and development (31). Integrated Organic Fertiliser Researchers and Promoters Association of Nigeria (IFORPAN) championed the organic agriculture movement in Nigeria and has promoted the use of organic fertilisers among indigenous farmers. After widespread adoption of organic practices by these organic farmers, INM attracted the attention of a research organisation

known as the National Horticultural Research Institute (NIHORT), which has since conducted extensive research on cucumber cultivation and organic fertilisation at their Bagauda WAVeP Project in Kano State (3). Initially, the institute focused on developing an organic method that would eliminate harmful chemical residues in soil and cucumbers grown under protected cultivation. Subsequent experimentation revealed that a combination of organic fertilisers, including decomposed farmyard manure (FYM), cow dung, poultry manure, and pig dung mixed at equal ratios and further combined with azotobacter culture, provided highly effective results. Investigations into preparatory procedures determined that pre-soaking the organic mixture for 10 days produced excellent outcomes well before the planting date (51). Soil analyses matured after seven days of application, and organic fertilisers lasted substantially longer in the soil compared to chemical alternatives. The beneficial effects of organic fertilisation on cucumber growth and development have been demonstrated by several studies.

9.2. Chemical Fertilizer Applications

Application of chemical fertilizers is a widely practiced method of supplementing soil nutrients to enhance plant growth and productivity. These fertilizers supply essential macro- and micronutrients in inorganic or synthetic forms that are readily available to plants shortly after application (52). Chemical fertilizers include nitrogen (N), phosphorus (P), and potassium (K) compounds, along with other vital mineral elements (53).

Under protected cultivation, chemical fertilization is frequently adopted to meet the elevated nutritional demands of cucumber (*Cucumis sativus* L.). The intense cropping systems and intensified growth conditions in greenhouse environments expedite soil nutrient depletion. The application of chemical fertilizers, therefore, serves as the main strategy for initiating crop growth and achieving optimal productive yields (3).

It is well documented that chemical fertilizers stimulate the vegetative growth and development of cucumber plants. Prompt availability of N, P, K, and other essential nutrients immediately supports various physiological processes, contributing to faster establishment, enhanced canopy development, and increased flower and fruit production. The high nutrient-release rate of chemical formulations generally favors an accelerated crop cycle, especially within the short growth periods preferred for cucumber production (54).

Conversely, prolonged and intensive use of chemical fertilizers is associated with numerous detrimental effects. Soil health deterioration is commonly reported following long-term application due to nutrient imbalances and disruption of beneficial microbial populations (37). Acidification and elevation of soil electrical conductivity are frequently observed, impairing nutrient uptake and overall soil functioning. Furthermore, environmental hazards, including the risk of nitrate leaching and groundwater contamination, pose serious challenges. These factors necessitate continued research toward sustainable fertilization regimes that mitigate the negative outcomes of exclusive chemical fertilizer use (55).

10. Challenges in Fertilization Practices

Soil degradation presents substantial challenges stemming from fertilization practices. Heavy application of chemical inputs typically accelerates degradation, yet overuse of organic sources can similarly elicit detrimental effects. Considerable attention must be afforded to incorporating sustainable fertilization strategies to prevent adverse impacts on soil quality (3). Excessive nutrient loading provokes ammonium toxicity and salt outline damage to plant roots. Nutrient runoff from unbalanced fertilizer application risks water contamination and eutrophication (56).

Consequently, the frequency of critical soil physicochemical properties such as organic content, microbial activity, pH, water, and oxygen levels diminishes under inappropriate fertilization regimes

(57). The degradation exacerbates the vulnerability of soil-plant systems to biotic and abiotic stresses. In view of the widespread adoption of properly formulated organic and chemical fertilizers, addressing these challenges assumes paramount importance in securing sustainable protected cucumber cultivation in the regions concerned (58).

10.1. Soil Degradation

Soil conservation is fundamental for ensuring agricultural productivity and sustainable development. In Morocco, productive arable land is estimated at about 8 million ha, and the average soil loss is 16 t ha/year. Agricultural production systems are reducing soil quality and water, as it is recognized that both are among the most precious natural resources for sustainable production of crops without jeopardizing the needs of future generations. Furthermore, water is the most limiting factor in farm plant production. Water scarcity limits agricultural activities in a large part of the world, including the Mediterranean basin (59). In Mediterranean semi-arid and arid regions, rainfall is limited and unevenly distributed throughout the year, with substantial periods of drought. More often than not, there is the irrigation of soils using chemical products or other compounds that are not biodegradable and accumulate in the soil, because the use of mineral fertilizer does not increase the soil organic matter content and degrade the soil structure, where soil particles aggregate in specific conditions. In addition, the interaction of soil with agrochemicals increases soil concentration of harmful substances in the air and water. Independent of fertilizer type (mineral or organic), the application of fertilizer leads to water pollution. Water and soil pollution caused by agriculture compromises the health of downstream ecosystems, and the toxic effects of herbicides damage useful soil fauna (60). Agricultural activities also lead to the salinization of water and soil. Soil abuse leads to its degradation and desertification, which limits the quality and quantity of yields. Soil is one of the important components of the natural environment, which is mainly affected by agricultural activities such as intensive cultivation, field cropping, mono-cropping, the use of agro-chemicals, overgrazing, and long drought periods. Soil degradation leads to mechanical obstacles and forms a direction of discouragement for sustainable crop production and global food security (3).

10.2. Nutrient Runoff

Nutrient runoff is the process by which excess nutrients from fertilizers, pesticides, soils, or animal wastes are carried away by water flow to nearby surface waters such as lakes and rivers. It is most critical during intense rainfall events or rapid snowmelt, when the volume and velocity of overland flow become large enough to carry significant amounts of soil and associated nutrients. Nutrient runoff occurs primarily during the precipitation period because runoff typically carries the highest nutrient concentration. In agricultural production, nutrient losses can occur through various pathways, but most importantly via surface runoff (3). Nutrient losses from agricultural land have many implications, including a decline in crop productivity and an increase in the eutrophication potential of nearby water bodies. The high nutrient concentrations in the runoff represent both economic losses and potential environmental pollution. Reducing nutrient losses in agricultural runoff will help protect water quality and ecosystem maintenance, as well as reduce unnecessary costs in the production process. The application of fertilizers for crop production increases crop yield by increasing the nutrient supply beyond what is available in the soil (61).

11. Future Directions in Cucumber Fertilization Research

Organic fertilizers improve soil physical, chemical, and biological properties by supplying essential nutrients. However, their nutrient release is slower than commercial fertilizers because organic matter degradation and nutrient transformation depend on soil conditions and microbial activity (41). Chemical

fertilizers provide a rapid nutrient supply, enhancing plant photosynthesis, growth, and fruit development. Organic fertilization improves growth parameters, including plant height, shoot diameter, internode number and length, and leaf size, as well as fruit size, weight, and yield 1. Incorporating organic fertilizers can enhance cucumber yield, reduce chemical fertilizer use, and increase vegetable quality and safety. Under protected cultivation, cucumber, spinach growth, yield, and quality respond better to organic than to chemical fertilization. Application of organic fertilizers fosters growth, yield, and economic profitability (62).

11.1. Innovative Organic Solutions

Organic amendments are essential for the sustainable protection of soil health in intensive agriculture. For the purse-string cheap technology, the abundant organic waste from home garden trees and hedge plants around the structure was evaluated for recycling nutrient cycling as a potting medium for the production of vegetable seedlings (63). Promising strategies for the use of organic fertilizers include nutrient recycling or the low-cost and rural effluents technology by improved field management, and possibly by the use of biofertilizers to help reduce reliance on chemical fertilizers. The combinations of inorganic, organic, and biofertilizers can help to improve soil fertility, provide balanced nutrient uptake, support higher cucumber productivity, and produce comparable yield as mineral fertilizer without adverse effect on soil properties (64).

Use of more adaptable organic fertilizers like vermicompost can also provide excellent soil conditioning and a sustained release of nutrients throughout the season (65).

Chemical fertilizer overuse – Estimating fertilizer consumption phased history can be beneficial to the economy. Climate change impact on crop productivity and nitrogen-fertilizer consumption appraisal in the agroecosystem of China can also directly assess the impact of changing nitrogen availability on net primary production (NPP) of the terrestrial ecosystem and carbon budget. Potential sources of nitrogen pollution and excessive use or misuse of chemical fertilizers can seriously damage the ecological environment and food safety (66).

Organic fertilizer should foster the production of not only high-quality but also high-quantity brands concerning cucumber agronomical standards.

11.2. Integrated Fertilization Approaches

Integrated fertilization methods combine the advantages of organic and chemical fertilizers to improve future sustainability (3). Such methods estimate dose quantities based on the nutrient uptake of the crop and conduct laboratory analyses of available nutrient levels in the soil. The base application of nitrogen, phosphorus, and potassium from organic fertilizer is combined with chemical fertilizer applications during crop development. Integrating organic fertilizer into chemical fertilizer regimes has also been shown to enhance crop productivity under a plastic film mulching irrigation regime (67).

12. Conclusion

Studies indicate that combined inorganic, organic, and bio-fertilizers can enhance cucumber earliness, productivity, and fruit characteristics through balanced nutrition and nutrient uptake. Incorporation of Azotobacter with organic inputs improves summer squash growth, yield, and quality by releasing growth-promoting compounds and improving soil structure. Fertilizer effectiveness increases when combined with bio-fertilizers, promoting soil health and crop yields. These insights suggest organic fertilizers constitute a reliable base input; however, sole application may restrict maximum cucumber yield.

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