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Recent Plant-Based Fertilization Approaches: A Review

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ABSTRACT

The reliance on inorganic fertilizers has been central to modern agriculture but has raised serious environmental and agronomic concerns, including soil degradation, nutrient imbalances, water contamination and greenhouse gas emissions. In response, plant-based fertilizers have gained attention as sustainable alternatives that enhance soil fertility, crop performance and ecological balance. This review synthesizes recent advances in plant-derived fertilizers, including duckweed, rice husk, fermented plant juice, sunflower residues and banana peels. These materials supply essential nutrients such as nitrogen, phosphorus and potassium, while also improving soil microbial activity, nutrient retention and crop yield. Studies demonstrate benefits such as reduced nitrogen leaching with duckweed, enhanced soil enzyme activity with rice husk biochar, improved flowering and photosynthesis with fermented plant juice and high potassium contributions from sunflower and banana residues. Despite promising results, challenges remain regarding nutrient variability, slow release rates, standardization and economic feasibility, which limit large-scale adoption. Innovations such as microbial enrichment and nano-formulations are improving efficiency, but further long-term field trials are needed. This review highlights both the agronomic potential and limitations of plant-based fertilization, emphasizing their role in sustainable agriculture and future integration into climate-smart farming systems.

1. Introduction

The intensification of agriculture over the past century has relied heavily on inorganic fertilizers to meet rising food demands. While effective in boosting yields, their excessive use has led to soil degradation [1], nutrient imbalances [2], water pollution [3] and greenhouse gas emissions, threatening both environmental health and long-term productivity. These challenges are further compounded by the urgent need to sustain global food security under the pressures of climate change, population growth and shrinking arable land.

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In response, research has increasingly turned toward sustainable nutrient management strategies, with plant-based fertilizers emerging as a promising alternative. Derived from green manures, composted residues, fermented plant extracts and seaweed-based products, they offer multiple agronomic and ecological benefits. Beyond supplying nutrients through processes such as nitrogen fixation and phosphorus solubilization, they enhance soil microbial diversity, improve soil structure, and reduce dependence on synthetic inputs.

Recent innovations including microbial enrichment, advanced extraction technologies, and nano-enabled formulations have further boosted their efficiency and versatility, positioning them as key components of climate-smart agriculture. However, despite this growing interest, the systematic evaluation of their performance, scalability and integration into modern farming remains limited. This review synthesizes recent advances in plant-based fertilization approaches, highlighting their potential roles in building sustainable and resilient agricultural systems.

2. Types of Plant-Based Fertilizers

2.1 Duckweed Fertilizer

Duckweed is one of small floating aquatic plants species. It is well-known to reduce algae bloom in aquatic environment. It serves benefits for poultry and also ruminants as a supplement protein feed. After being tested, duckweed has a potential as plant-based fertilizer with the comparable Nitrogen, Potassium and Phosphorus contents to manure-based fertilizer. It might be a good source of soil amendments and replace inorganic fertilizer and decrease the long term impacts. It also might be a perfect soil amendment that can hold the nutrients from leaching. There were studies that exploring about the potential of duckweed as fertilizer.

Kreider *et al*., [4] explored nutrients retention in *Sorghum bicolor* L field applied with the duckweed as soil amendments. The duckweeds were collected in the open pond. After strained, the duckweeds were dried at 60◦C in convection oven. Metal contents analysis was conducted using ICP-AES. The results for N, P, K and C were 75mgkg^{-1}, 82 mgkg^{-1}, 0 mgkg^{-1}, and 0 mgkg^{-1} respectively. The dried duckweeds were applied into the soil and commercial fertilizer as a control. It showed that dried duckweeds only cause 2% of N leaching while the control leached the N significantly for about 60%. Plus, dried duckweeds can retain almost 30% of total mineral. Pulido *et al*., [5] stated that duckweed can significantly enhance P uptake in sorghum. The finding indicates that, dried duckweed can be a good source and sustain the amount of N in the field.

A study was conducted to evaluate the performance of lettuce applied with duckweed as fertilizer at different treatments [6]. No fertilization applied as a control. Duckweed applied at 60kgha^{-1}, 120 kgha^{-1} and 180 kgha^{-1} of nitrogen, urea 60 kgha^{-1} nitrogen and commercial organic fertilizer at 60 kgha^{-1} nitrogen. The study had measured several parameters including fresh and dry weight, leaves number, minerals contents, nitrates, chlorophyll, carotenoids and nitrogen use efficiency. The results showed that duckweed significantly increased lettuce by 50% compared to control and inorganic fertilizers. There was no difference in yield and quality among varying amount of duckweed applied.

Duckweed extracts had been tested on the growth of tomato plants [7] at different concentration; 0.1, 0.5 and 1.0%. The results show that the number of leaves, the fresh and dry weight and root traits improved compared to control. The extracts also have increased the pigment and flavonoid contents.

While the research demonstrates the performance of duckweed on different crops, there is lacks of comprehensive analysis of the economic implications on the farmers such as cost-benefit analysis and market acceptance of using an unconventional fertilizer like duckweed. Plus, there are a lot of duckweed species, the study of variability in nutrient contents of the species are still limited and more studies are required to explore how different preparation techniques affect the nutritional value across species.

2.2 Rice Husk Based Fertilizer

Rice husk fertilizer is one of the new innovative approaches for sustainable agricultural practices. With the abundant of rice by products, using them to address the environmental concerns is a good move. Rice husk-based fertilizers can be derived through various methods such as fermentation, biochar production and incorporate with nanotechnology.

As an organic fertilizer, 30% of rice husk were mixed with 10% of chicken manure, 10% of duck dung, 10% of pig manure, 7 % of straw and 6% of sludge were composed [8]. The mixture offers high fertilizer efficiency. This easy process makes it suitable to practices by farmers especially smallholder farmers. For example, RH amended soil gives the highes lettuce growth and production [9]. A similar study by Akumuntu *et al*., [10] applied RHB at 0-1.5%. All RHB concentration did not have effects on soil pH. However, the enzyme activities escalated after 28th day of lettuce growth. The root weight and leaf numbers also increased.

Recently, a slow-released fertilizer and immobilization of cadmium was derived using rice husk, known as rice husk biochar-based fertilizer (RHBF). Tan *et al*., [11] have developed four types of RHBF: blended, soaked, high-pressure soaked and pure rice husk biochar coated fertilizer. The nutrient slow-released of these four RHBF was compared using hydrostatic and soil column intermittent leaching methods. This study found that RHBF released nutrients slower and the leaching of rates of nitrogen significantly lower than the conventional fertilizers. Among these four, the high-pressure RHBF released nutrients slowest. The application of this RHBF resulted in increase in nutrient use efficiency, grain yield and photosynthetic characteristics. Additionally, RHBF reduced the cadmium mobilization about 80% compared to conventional fertilizers. Hence, it has potential to improve crop yield and also soil health.

The long-term impacts of RHBF on soil health and microbial communities remain unexplored, and its potential for market adoption has not been sufficiently analyzed.

2.3 Fermented Plant Juice

Fermented plant juice (FPJ) is a technique involving the fermentation of plant materials to promote plant growth and improve soil health. FPJ can be applied as a fertilizer or soil amendment and a wide range of plant species have been utilized to treat various crops. Plant parts with high nutrient content such as stems, leaves, rind, peels and fruit skins can serve as raw materials [12]. In addition to fresh plant materials, domestic plant-based waste can also be converted into FPJ, making it a sustainable approach to waste utilization [13]. Through fermentation, these materials and beneficial microorganisms like lactic acid and yeast [14] are transformed into nutrient-rich solutions that support crop productivity.

FPJ is particularly effective in rehabilitating degraded soils impacted by prolonged chemical fertilizer use [15]. The soil fertility can be restored. Other than as soil amendments and liquid fertilizers, FPJ can also be applied as a foliar spray, delivering nutrients directly to plant leaves for rapid uptake. Direct uptakes by plants are beneficial in alleviating nutrient deficiencies in crops [16]. The composition of FPJ varies according to the raw materials employed; common formulations involve the fermentation of plant residues with brown sugar and water to produce a stable and effective fertilizer [15]. To further enhance its nutrient profile and efficacy, supplementary components such as humic acid, poultry manure and trace microelements may be incorporated [17].

Several studies have highlighted the potential of FPJ. The application of fermented plant juice (FPJ) and fermented fruit juice (FFJ) has been shown to promote earlier flowering and fruiting in tomato plants through increased auxin production and the supply of essential nutrients. In a study involving five treatments of FPJ from water spinach and bamboo shoots and FFJ from pineapple and banana, plant performance was assessed based on flowering and fruiting time, total soluble solids after 10 weeks, photosynthetic rate and transpiration rate [18]. Both FPJ and FFJ treatments accelerated reproductive development compared to the control, with significantly increases in total soluble solids after 10 weeks. FPJ from water spinach was more effective in promoting vegetative growth, while FFJ from pineapple enhanced reproductive development. Photosynthetic rates improved in all treatments except T3, and transpiration rates increased only in T4 compared to the control. These results indicate that FPJ and FFJ can improve crop growth and yield while supporting sustainable agricultural practices by enhancing plant physiological performance and utilizing plant-based residues as fermentation substrates.

Similarly, fermented alfalfa brown juice (BJ) has shown to significant enhance the growth and development of sweet basil (*Ocimum basilicum* L.) [16]. In a study comparing foliar applications of fermented BJ at concentrations of 0.5%, 1.0% and 2.5% with a control (0.0% BJ), the 0.5% treatment produced the most pronounced improvements. Application of fermented BJ increased stem and root lengths, fresh masses of stem, root and leaves, stem and root volumes, and leaf area. It also elevated the contents of chlorophyll *a* and *b* and relative chlorophyll levels (SPAD value), indicating enhanced photosynthetic capacity. While control plants produced more leaves, their leaf size was smaller compared to treated plants. These results demonstrate the potential of fermented BJ as an effective bio-stimulant for improving vegetative growth and physiological performance in crops.

A key limitation of fermented plant juice (FPJ) is the variability in nutrient composition, which can result from differences in plant materials and fermentation processes. Consequently, the nutrient profile may not be equally suitable for all crops. For this reason, FPJ is most effective when used as part of an integrated crop management strategy in combination with other sustainable agricultural practices.

2.4 Sunflower Fertilizer

Other plant-derived materials, such as sunflower byproducts, also show promise as fertilizer components. Sunflower stalks, discs, seed cakes and husk ash are rich in essential nutrients and can be processed into organic, chemical or slow-release fertilizers suited to various crop stages and soil conditions. Husk ash is particularly valuable for its high K, P, Ca, and Mg content. Fertilizer formulations often combine sunflower residues with animal manure and inorganic sources, such as urea, calcium magnesium phosphate and sulfur fertilizers, to meet nutrient demands throughout the growth cycle.

A study by Ninkov *et al.*, [19] stated that sunflower husk ash is a nutrient-rich byproduct containing significant amounts of P (10.94% P_2O_5), K (25.84% K_2O), Ca (19.07% CaO), and Mg (18.58% MgO), along with micronutrients such as Zn, Cu, Co, Mn, Fe and Mo. Its composition makes it suitable for the fertilization of a wide range of crops. A study on its utilization focused on producing complex fertilizers of the 0-6-13 grade, optimizing granulation parameters such as recycling and moisture content, ingredient ratios and the use of additives. Binding agents, including sugar factory lime, molasses, and urea formaldehyde resin were found to improve granulation efficiency. Product quality was evaluated through standard methods, assessing chemical composition, static crushing strength of granules, granulometric distribution and pH of a 10% solution. The findings confirm the potential of sunflower husk ash as a valuable raw material for sustainable fertilizer production.

Gul [20] analyzed the nutrient composition of ashes derived from burning sunflower plant wastes from ten hybrid varieties (Coral, Pioneer63F73, PioneerP64LL05, Pioneer64LC108, Goldsun, Şems, Aga1301, Duna, Bosfora, and PioneerPR64G46). The aim was to assess their potential use as natural fertilizers, particularly in soils deficient in key nutrients. Field experiments were conducted in Kavak, Samsun Province, Turkey, using a randomized block design with three replicates. After harvest, plant residues (stalks, leaves, heads) were burned, and the resulting ashes were analyzed for B, Mg, P, K and Ca using ICP-MS. Results showed that K was the most abundant nutrient (23.35–37.69 g kg^{-1}), followed by Ca (20.85–26.64 g kg^{-1}) and Mg (8.56–17.27 g kg^{-1}), with lower levels of P (1.64–7.27 g kg^{-1}) and B(0.12–0.25 g kg^{-1}). The highest B and Mg concentrations occurred in PioneerPR64G46, the highest P and Ca in PioneerP64LL05, and the highest K in Pioneer64LC108. These findings highlight sunflower waste ash as a rich source of essential macro and micronutrients, particularly K and P, making it suitable for use as a low-cost, sustainable fertilizer. The study emphasizes its potential for improving soil fertility, especially in P and K deficient soils, while reducing dependency on synthetic fertilizers. However, nutrient variability among varieties suggests that further research is necessary to optimize its agricultural application.

2.5 Banana Peels Fertilizer

Banana peels are often discarded despite containing high levels of essential plant nutrients. The composition is particularly rich in K, Ca , P, Mg and S, all of which are vital for plant growth. It contains cellulose, hemicellulose, pectin, lignin and growth stimulants such as l-tryptophan which can enhance seed germination and improve overall plant health [21].

Fertilizers from banana peels can be produced through microbial fermentation, composting, biochar production or blending with other organic materials [22]. Liquid organic fertilizers (LOF) derived from banana peels have demonstrated positive effects on mustard greens and pak choy, resulting in increased plant height, leaf number, and fresh biomass when applied at optimal dosages [23]. Blending banana peels with other residues, such as orange peels, has been shown to further enhance plant growth performance [24].

In some cases, banana peel-based LOF produced limited improvements. For instance, applications to okra plants did not yield significant growth differences compared with inorganic fertilizers, possibly due to lower nutrient concentrations [25]. The method of application, including top dressing or basal dressing, also influences effectiveness [24].

The table summarizes findings from recent studies on the effects of banana-based fertilizer on various crops. Reported benefits include improvements in plant height, leaf number, biomass, nutrient uptake, yield and seed quality, though results vary depending on crop type and treatment. Some crops showed no significant growth differences compared to controls, indicating that responses are species-specific. Overall, these studies highlight the potential of organic fertilizers to enhance crop performance while promoting sustainable agricultural practices.

Table 1
Crop responses to banana-based fertilizer treatments in recent studies

Crop	Results	Author (s)
Tomato	Increased nitrogen (16-31%); Increased potassium (12-24%) in soil; Higher N, K, P in plants; No significant difference in fruit yield; Lower total salts in fruits	[26]
Pepper (*Capsicum annuum*)	Increased plant height; Increased number of leaves; Increased fresh dry weight	[27]
Okra (*Abelmoschus esculentus*)	Increased plant height; Increased number of leaves; Increased stem girth	[28]
Pepper (*Capsicum frutescens*)	Higher fruit yields; More flowers per plant; No significant difference in height	[29]
Green gram (*Vigna radiata*)	Higher seed; Increased number of pods; Increased pod weight per plant.	[30]
Green onions	No significant difference in growth compared to control.	[31]
Ladyfinger (*Abelmoschus esculentus*)	Faster daily growth; Increased stem and leaf height; No pest attacks	[32]
Flax (*Linum usitatissimum*)	Increased plant height; Increased shoot/root weight; Increased leaf area	[33]
Fenugreek, tomato	Higher crop yield; Higher germination in the first week	[34]
Soybean (*Glycine max*)	Increased growth parameters; Higher seed yield; Improved pigments and biochemical in seeds.	[35]
Ulam Raja (*Cosmos caudatus*)	Higher shoot and root length; increased number of leaves.	[36]

3. Limitation of Plant-Based Fertilizers

Despite the growing body of evidence supporting plant-based fertilizers, several limitations hinder their widespread adoption. A major challenge is the inconsistency in nutrient release rates, which can lead to deficiencies or delayed availability compared with synthetic fertilizers [37]. This variability is further complicated by the absence of standardized formulations, application guidelines, and long-term, multi-site trials, which reduces cross-study comparability and weakens the development of universal recommendations [38].

Environmental trade-offs also remain unresolved. While plant-based inputs can reduce nitrogen losses and enhance soil carbon sequestration, some studies report increased greenhouse gas emissions when organic fertilizers replace mineral inputs [39]. The scarcity of long-term field experiments and the neglect of regional variability in soils and climate further limit the reliability of sustainability assessments [40]. In addition, the complexity of microbial interactions in bio-fertilizers is often underexplored, leading to inconsistent performance across environments.

Economic feasibility is another critical yet under-investigated dimension. Most cost–benefit analyses are short-term or small-scale, with few extending across multiple cropping cycles [41]. High production and transportation costs, labor-intensive application, certification barriers, and limited farmer acceptance continue to impede adoption. Although integrated nutrient management is frequently recommended, empirical evidence on its optimal implementation remains fragmented.

Finally, methodological heterogeneity across studies including differences in duration, scale, crop type, and measured parameters combined with a reliance on greenhouse or microcosm experiments, limits the applicability of findings to real-world farming systems [37]. Moreover, the limited integration of agronomic, environmental, and socio-economic dimensions in single frameworks constrains holistic evaluations of plant-based fertilizer sustainability [41].

4. Conclusions

Plant-based fertilizers represent a promising pathway toward sustainable agriculture by reducing reliance on synthetic inputs, enhancing soil health, and supporting crop productivity. Evidence from recent studies demonstrates significant benefits, including reduced nutrient leaching, improved microbial activity and enhanced crop performance across diverse farming systems. However, the results also reveal variability in nutrient composition and yield responses. These inconsistencies, combined with the lack of standardized formulations, limited long-term field trials and unresolved economic considerations, currently restrict their large-scale adoption.

To realize their full potential, future efforts must integrate plant-based fertilizers into holistic nutrient management frameworks, supported by innovations such as microbial inoculants, nano-enabled formulations and circular economy approaches that valorize agricultural and food residues. Policy support, farmer awareness programs, and robust cost–benefit analyses will be crucial in overcoming adoption barriers. Ultimately, plant-based fertilizers hold strong potential to reconcile the dual goals of productivity and sustainability, positioning them as an essential component of climate-smart agriculture and global food security strategies.

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