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Review

Preparation of Biofertilizers from Banana Peels: Their Impact on Soil and Crop Enhancement

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Abstract: Disposing of banana peels (BPs) as bio-organic waste is an environmental challenge. Rich in potassium, BPs are often discarded despite their agricultural value. Reports on the valorization of BP are increasing, but no review has focused on BP fertilizer preparation methods. This study aims to review and analyze these methods to guide researchers and agriculturists in optimizing BP utilization, promoting sustainable waste management, and effective agricultural practices. This review has uncovered significant findings. A composite of banana and orange peels emerged as the most favoured and widely used approach, closely followed by dried BPs. This study highlighted the substantial impact of fertilizer application methods such as top and basal dressing. Most of the results revealed that the peels significantly improved the growth parameters of various plants. However, for biochar, the plant height was insignificant between treatments, further emphasizing the importance of the application method used. Banana peels are a valuable resource for biofertilizer synthesis. The banana–orange peel composite exhibits outstanding fertilizer properties. More new studies should go beyond the seedling stage, especially to harvest. This would give more information on the performance and viability of BP fertilizers.

Keywords: fertilizers; banana peels; preparation methods; potassium; plant height

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1. Introduction

Demand for food is driven by an ever-growing human population and changing eating habits [1]. Such factors contribute to food shortages and food insecurity, which threaten the livelihood of humans [2,3]. Researchers have developed alternative strategies to grow crops faster and enrich the soil with the necessary nutrients using chemical fertilizers to meet the demands for food [4–7]. Chemical fertilizers are industrially manufactured to contain a specific number of nutrients required by the soil to enhance plant growth [8]. The most common chemical fertilizer is NPK, i.e., nitrogen, phosphorus, and potassium, which contains nitrogen, phosphorus, and potassium in different ratios. Superphosphate, urea, and potash are also popular. For a substance to be classified as a fertilizer, it should contain a minimum of 5% N, P, or K, known as the primary or macro-nutrients [9,10]. They play a vital role in enhancing plant development and growth. Indeed, their functions and how they contribute to soil fertility are well documented [11–14]. However, due to their efficiency in increasing soil fertility and enhancing plant growth, chemical fertilizers are often applied in excess [15]. As a result, they cause adverse effects on the environment, such as global warming, biodiversity loss, depletion of the stratospheric ozone layer, and eutrophication [9,16,17]. Besides their excessive use, their huge procurement, shipping, and transportation costs make them unsustainable [18]. There are several strategies that researchers have developed to reduce and circumvent the effects that synthetic fertilizers have on the environment. These include applying organic-based fertilizers such as fruit peels (e.g., banana peels) [19], nano-fertilizers [20], using improved methods of application [21], and slow-nutrient-release fertilizers [22–24].

Organic fertilizers are naturally occurring fertilizers derived from agricultural waste (plant and animal waste) [16]. Animal waste or by-products include cow dung, slaughterhouse waste, eggshells, manure (chicken, horse, goat, sheep, and rabbit), urine, bone meal, and fish emulsion [25,26]. Plant waste materials include straw, corn stalks, livestock feed (alfalfa meal), cottonseed meal, molasses, green manure, duckweed kelp seaweed, and used tea waste. Various parts of the plant, such as the leaves and (pseudo) stem, can be used as a fertilizer. Organic fertilizers consist of moderate amounts of the essential nutrients for plant growth, i.e., nitrogen, phosphorous, and potassium [27]. They are environmentally friendly, ensure the conservation of biodiversity, are economical, and easily attainable since they are acquired from agri-waste, compared to inorganic fertilizers, which are made from various synthetic chemicals [16]. Through their application, the depletion of the rate of the application of synthetic fertilizers and a reduction in their adverse effects are conceivable [28]. Due to these advantages and others, replacing inorganic fertilizers with organic fertilizers has received worldwide attention from scholars and farmers. There has also been a growing trend among consumers toward buying crops grown by following organic farming practices [29]. Furthermore, fruit and vegetable waste has gained popularity as an organic fertilizer due to its ability to enhance plant growth and improve soil fertility.

This waste is mostly peels generated after the consumption of fruits and vegetables. Examples include bananas, oranges, pomegranates, tangerines, potatoes, and lemons.

This review focuses on banana peel-based fertilizers and will include other fruit peels or agri-waste mixed with those of bananas to make composite fertilizers. Thus, this review article aims to give an in-depth overview of the preparation methods of banana peel-based fertilizers due to their high potassium content. There are also limited review articles that solely focus on using banana peels as fertilizers. Furthermore, the methods of preparing the peels, and other factors, such as the decomposition time of the peels during their preparation, influence the level of nutrients extracted from this organic waste. Therefore, this study shows the most utilized method to prepare the peels, which is also regarded as the best method. The impacted parameters, such as plant height, germinating rate, and number of days to germination, are discussed and also used as a measure of the efficiency of the fertilizers.

2. Method

a. Relevant databases and information sources: The literature search for research articles reporting on the preparation and application of banana peels as fertilizers was carried out on reputable academic databases: PubMed, ScienceDirect (Elsevier), Springer, Proquest, and Scopus. Google Scholar, ResearchGate, and the Directory of Open Access Journals were also utilized to access relevant studies.
b. Relevant search terms for the topic of interest were considered: "banana peels-based fertilizer", "banana peels-based composite fertilizer", "agricultural waste fertilizer", "valorization of banana peels", and "preparation methods of banana peels".
c. Publication timeframe: The selected articles were published between 2012 and 2024 and in English.
d. The selection of references for this review was guided by an analysis of their content: More than 146 articles were identified based on their abstracts, and only 126 of those publications were included; 7 studies focused specifically on the use of banana peel-based fertilizers, 9 studies focused on banana peel composite fertilizers, and 5 studies focused on banana peels transformed into biochar for fertilizer applications.

3. Banana Peels

Banana is a fruit grown in almost every part of the world, especially in tropical and subtropical regions [30]. It belongs to the Musaceae family, originating in Southeast Asian countries, and possesses more than 1000 varieties [31]. It is available throughout the year and has become one of the most abundant fruit crops consumed globally, with yields of up to 116 million tonnes from 2017 to 2019 [32,33]. The countries that grow the most bananas are India, China, Indonesia, Brazil, and Ecuador [34]. Its varieties contain different properties depending on their size, colour, and firmness. Conventionally, banana is curved, fleshy, yellow after maturation, and brown when ripe [35].

The fruit comprises pulp and peel, with the latter accounting for 26–30% of the total fruit weight [35–37]. Since banana fruit is consumed in large quantities globally, the banana peel (BP) waste generated amounts to up to 36 million tons annually [38,39]. The peels are commonly disposed of in landfills, causing serious environmental concerns and costs associated with their disposal [40]. They accumulate in large amounts and contribute to methane gas levels in the atmosphere, a greenhouse gas [41]. Furthermore, landfill leachate tends to pollute surface and groundwater, endangering the environment and human life. However, these peels contain a plethora of nutrients (Table 1) that can be recovered for use in soil amendment.

Banana peels have been used for decades, and some of their recent applications are attributable to technological advances. Traditionally, this banana by-product was used for acne, warts, hair, face masks, and food wrappings [42–44]. Burns, ulcers, anemia, diarrhea, excessive menstruation, coughing, snakebites, and inflammation were treated using these peels [39,45–47]. Modernization and technological advances have enabled researchers to extract some of the compounds and elements found in the peels for use in various disciplines, as summarized in Figure 1.

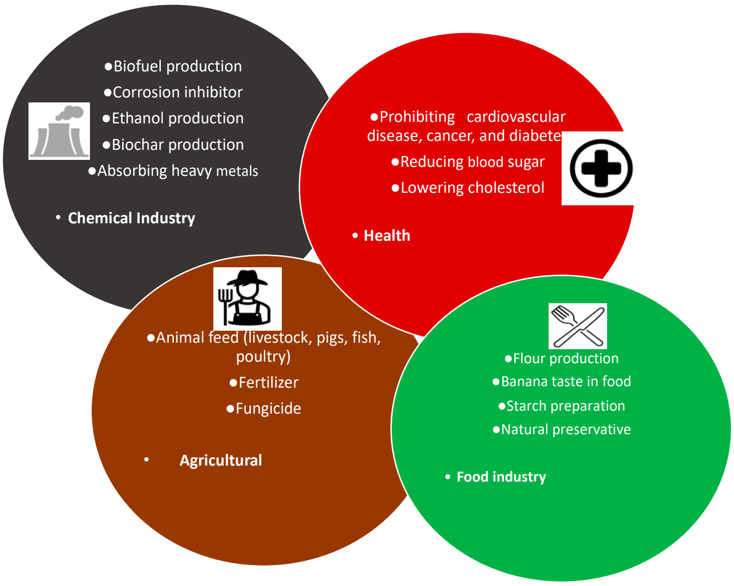

Figure 1. Modern applications of banana peels, categorized to sectors.

Table 1. Nutritive components of banana peels (*Musa sapientum*) [39,48–50].

Nutritional Component	Content (%)
Carbohydrates	59–67
Proteins	0.9–5.3
Starch	3.5–6.3
Fibre	19.2–31.7
Crude fat/lipids	1.24–5.93
Ash	3.95–9.60

Banana peels can be used to remove cyanide from contaminated wastewater [51]. They are utilized as a feedstock for biofuel production [52] and ethanol production [53]. The peels' adsorption properties enable their application in steel corrosion inhibition [54]. The peels are rich in phenolic compounds, which have multiple health benefits, such as prohibiting cardiovascular disease, cancer, and diabetes, when incorporated into food. Their antifungal properties enable treatment against various fungi [44,55–57]. They are directly used as feed for animals such as livestock, monkeys, fish, poultry, and pigs because of their high fiber content [58,59]. Recently, the cover or shell of the banana fruit has received considerable recognition in farming as a green or organic fertilizer due to its high potassium content and minute amounts of other nutrients required by the soil, as seen in Table 2.

Table 2. Elemental composition of BPs [60].

Element	Content (mg/100 g)
Potassium	475.6
Calcium	323.0
Sodium	148.9
Phosphorous	122.5
Iron	0.40
Manganese	69.0
Zinc	4.55

The benefits of using BPs as a fertilizer include reducing the costs associated with transportation and dumping the peels, conserving soil biodiversity, improving plant yield, and preserving the environment and protecting it against adverse effects caused by chemical fertilizers. It also reduces the bad odour resulting from the peels decomposing, expanding and adding more value to the banana industry. Additionally, it contributes to sustainable and organic farming. The avenues taken to prepare banana peel-based fertilizers are discussed in the next section.

3.1. Banana Peel-Based Fertilizers

The high potassium (K) content in this under-utilized renewable resource has made it an attractive fertilizer to agricultural scientists. Various recipes and methods exist to utilize BP or extract its high potassium content (Figure 2). BPs can be converted to ash by combusting the peels in open flames (Figure 2a). Alternatively, the peels can be pyrolyzed at elevated temperatures in an inert atmosphere to convert them to biochar (Figure 2b).

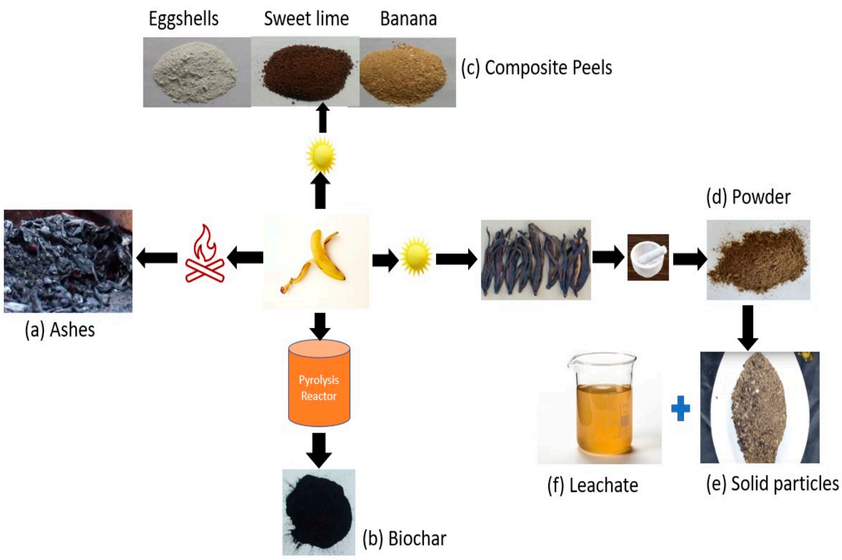

Figure 2. Various banana peel-based fertilizer preparation methods, including (**a**) ashes, (**b**) biochar, (**c**) composite peels, (**d**) powder, (**e**) extract, and (**f**) filtrate.

Banana peels can be dried along with other agro-waste materials such as orange peels, eggshells, tangerine peels, moringa leaves, cow dung, and synthetic fertilizers and mixed to form a composite fertilizer (Figure 2c). In this way, a superior organic fertilizer with synergistic capabilities is formed. The dried peels can be crushed and utilized as a standalone fertilizer (Figure 2d). Most of the techniques described above result in a powdered material. A liquid extract can also be prepared by dissolving the dried peels in a solvent. The solvent is filtered, and the resulting solid components (Figure 2e) and the leachate (Figure 2f) can be used as a liquid and powder fertilizer. Liquid fertilizers can be synthesized by crushing fresh banana peels and using an extracting agent to extract their potassium in the presence of heat. Subsequently, the thick mixture is filtered and a liquid fertilizer remains.

3.1.1. Effect of Wet and Dried Banana Peels on Plant Growth Parameters

The method used to prepare the peels for soil enrichment and crop growth influences their performance as an organic fertilizer. As demonstrated in Figure 2, peels can be used as fertilizers by drying them in the sun for a certain period, crushing them into a powder, and mixing them with the soil. They can also be dissolved in a solvent like water after grinding, and then mixed with the soil. Furthermore, soil and water can be used as decomposition media for PBs. In such a case, peels are cut into smaller pieces or ground, and then introduced into the soil or water and kept within it for a period of time before being applied as fertilizer.

In one such example [61], the focus was placed on uncovering the detailed dynamics of banana peels' decomposition over different periods (2, 4, and 6 months) within water and soil matrices. This study also delved into the momentous impact of the leachate on the germination rate and growth of *Pisum sativum* L. plants. To decompose them in water, the authors placed 150 $\pm$ 1.00 g of BPs in mesh bags and separately introduced them into 20 L polyethylene buckets filled with 15 L of water from a well. For their decomposition in soil, the peels were dried between temperatures of 15 and 35 °C and then chopped and placed into pots containing 5 kg of garden soil. To further enrich the study, *Pisum sativum* seeds were sterilized with a 4% sodium hypochlorite solution, magnetically stirred for 30 min, and rinsed with distilled water. Subsequently, 20 seeds of *Pisum sativum* L. were planted in pots containing BPs that had decomposed for different periods in soil and water or pots irrigated with leachate from the banana peels. Table 3 summarizes the conditions, properties, and effects on plant height of the wet and dry BP fertilizers reviewed in this section. Plant height was the response parameter chosen to measure the impact of the fertilizers since it was found to be the common growth parameter among the studies.

Table 3. Plant heights and germinating rates of various crops treated with banana peel-based fertilizers.

Test Crop	Elemental Composition	Working Conditions	Germinating Rate/Days	Plant Height	Experiment Duration	Ref.
Green pea	BP: N = 21 mg/g Dw	BP pH = 5.74 Soil pH = 7.77	~94.59% in 5 days	75 cm	3 months	[61]
Potato Pea	Soil + BP: N = 0.08% P = 18 ppm N = 88 ppm Ca = 4 meg/L	Soil + BP: pH = 8.89 EC = 1.14%	7 days 4 days	10.62 cm 7.5 cm	3 months	[62]
Fenugreek	Soil: NPK = 2.7, 2.4, 1.2 NPK = 3.6, 2.9, 1.7 NPK = 4.7, 3.5, 2.1	-	-	-	45 days	[63]
Okra Radish	- BP:	-	-	17 cm 6.5 cm	14 days	[39]
Onion	K = 78.10 mg/g Mn = 76.20 mg/g	-	-	Onion leaves = 15.1 cm	7 days	[64]

Table 3. *Cont.*

Test Crop	Elemental Composition	Working Conditions	Germinating Rate/Days	Plant Height	Experiment Duration	Ref.
Tomato Fenugreek	Na = 24.30 mg/g Ca = 19.20 mg/g Fe = 0.61 mg/g BP K = 78 g/kg Fe = 0.6 g/kg	Clay loam soil: Sand = 25% Silt = 37% Clay = 38% Bulk density = 1.1 g/cm^3 Conductivity = 0.69 cm.h	7 days	-	7 days	[65]

Table 4 summarizes the germinating rates and plant heights obtained with peels decomposed for different lengths of time and in different mediums. It can be seen from the table that the best germinating rates for peels decomposed for 2 months were obtained from peels in a soil medium. For peels used after 4 months of decomposition, the BP decomposed in water and its leachate had similar germination rates; however, they were higher than that of peels decomposed in soil (Table 4). The overall highest germinating rate (~94.59%) was obtained from peels decomposed for 6 months in water. Interestingly, the peels without decomposition were shown to have high germinating rates compared with some of the decomposed peels. The peels decomposed in soil yielded higher plant heights than all other mediums; 75 cm after 90 days of planting. This observation is supported by the work of Frink et al. [66], who established that the nutrients available in organic fertilizers are best liberated after decomposition for extended periods. However, in the work of El Barnossi et al. [61], the growth of the plant height was least improved after extended periods, since it decreased with an increase in decomposition time. The authors found that the best decomposition period of BP for crop growth is two months in a soil medium. However, peels can also used without decomposition, as these showed good germination rates and plant heights.

Table 4. Germinating rates and heights of *P. sativum* plants treated with BP decomposed in different mediums and for different decomposition times [61].

Duration (Months)	Soil-Decomposed Peel		Water-Decomposed Peel		Leachate		Peels Without Decomposition (%)	
	Germinating Rate (%)	Height (cm)	Germinating Rate (%)	Height (cm)	Germinating Rate (%)	Height (cm)	Germinating Rate (%)	Height (cm)
2	83.10	75.00	76.06	51.66	76.06	55.76		
4	66.20	58.33	83.74	50.66	83.74	53.43		
6	67.58	49.33	94.59	43.40	78.39	45.26	83.33	65.00

Researchers have studied the merits of using various organic materials as fertilizers. These materials include eggshell powder, wood ash, fruit and vegetable leaves, etc. In one such study by Wazir et al. [62], the materials investigated included tea waste and banana peel powder. The BPs were dried in the sun, cut into small pieces of ~1 cm^3, and 20 g of the resulting dried peel powder was mixed with pot soil (4 kg). The treated soil was left for 60 days before seed sowing to decompose and allow nutrient release. Upon analysis of the soil samples, the researchers observed that they exhibited alkalinity, with a pH of 8.98, and key nutrients such as nitrogen, phosphorus, potassium, and calcium at 0.08%, 18 ppm, 88 ppm, and 4 meq/L, respectively, as seen in Table 3. Unlike El Barnossi et al. [61], who reported the germination rate and the number of days to germination, Wazir et al. [62] only reported the time it took for the seeds to germinate. It was found that for the potato and pea to germinate it took 7.75 and 4 days, respectively. In terms of plant height, rapid growth was observed after 60 days since the minerals were released slowly during the growth process. Compared with the other organic fertilizers the researchers studied, the shortest period of germination was obtained from BPs. The authors attribute this to the presence of phosphorus and calcium in the BPs, which play a significant role in seed germination, viability, and the early maturation of plants. Other growth parameters, such as leaf and branch number, were significantly enhanced compared with the control. The same trend was observed for both plants' yield parameters, such as pod length, tuber weight, etc. Used tea waste was shown to perform better than other organic waste materials. Therefore, composite fertilizer comprising BPs and tea waste has a high potential to enhance crops' growth and yield parameters.

3.1.2. Dried Banana Peel-Based Fertilizers

In a quest to determine the impact of dried BPs on the growth of fenugreek plants, Mercy et al. [63] prepared and applied six fertilizer formulations. The formulations were grouped into two methods: powder extracts and powders. The peels were cut into small pieces, air-dried in sunlight for 20 days, ground, and sieved. The powder extracts were prepared by dissolving 1 g, 3 g, and 6 g of BP powder in 100 mL, 300 mL, and 600 mL of distilled water, respectively. The mixtures were stirred for three days using a magnetic stirrer. For the powder method, formulations 1, 2, and 3 contained 1 g, 3 g, and 6 g of the BP powder, respectively. Each formulation had three replications, and a control was maintained for 15 days. After this period, 100 fenugreek seeds were sown and irrigated daily. The authors measured plant height 45 days after inoculation; the study revealed that the plant height was higher for the powder extract. The crops were produced quicker using both methods, with a larger number of fenugreek vegetables produced than in the control soil. Formulation 1 was found to be the most suitable fertilizer for both methods. This formulation was tested on different crops (rice, mustard, and rye) and improved growth was observed in all the test plants compared to the control. Although the authors did not justify the higher plant height seen from the powder than powder method extracts, it could be that in the powder extracts, the nutrients are in liquid form and are readily available for use by the plant. Meanwhile, the powders must be broken down by microorganisms in the soil and dissolved before their nutrients become available. This can also explain why the 1 g performed better than the 6 g, i.e., 1 g decomposed faster than the 6 g. Elucidation of the type of interaction that liquid powder extract and powder organic fertilizers have with the soil and plant can pave the way toward understanding their influence. Interestingly, other studies have shown that plant health and the growth parameters of BPs become better with the amount of BP powder applied [67]. Characterizing the banana powders in terms of the chemicals and minerals present could help us understand contradicting performances, because banana peels from different regions/countries could have varied chemical properties.

To address these chemical differences, highly developed technologies are used, including Nuclear Magnetic Resonance (NMR) and infrared (IR) and X-ray spectroscopy, which are capable of providing critical insights into the composition of the molecules and elements of banana peel-based fertilizers [68–70]. For instance, NMR is capable of identifying specific metabolites and bioactive compounds in banana peels, especially phenolics and carotenoids, and their nutritional value [71]. The detailed molecular profiling obtained aids in explaining the differences in the release of nutrients, rate of degradation, and the overall efficiency of fertilizers [72]. FTIR analysis has identified critical functional groups in banana peels that are essential for the binding and release of nutrients, including phenols, amino acids, and alcohol [73]. X-ray spectroscopy, on the other hand, provides precise data on elements by illustrating the concentration of essential plant nutrients, which are critical for plant health [74].

The importance of such results lies in their ability to standardize and improve the efficiency of banana peel fertilizers for improved agricultural results. Seasonal differences have a meaningful impact on the chemical make-up of banana peels, especially their key metabolite levels, and this was shown by a study conducted by Cardoso et al. [69].

Therefore, for a better understanding of these chemical variations, employing a combination of the mentioned technologies, i.e., NMR, X-ray, and IR, for the characterization of banana peels from different regions is worthwhile. This will also assist in adjusting the processing methods used to ascertain consistent and maximized fertilizer performance. Ultimately, these data will equip us with the production of more effective organic fertilizers, modified for the release of nutrients in the best possible way, which will improve soil health and enhance crop yields.

Different types of fertilizers are used to enrich the soil [24], and they influence the properties of soils [21] and the growth of plants [75]. They include the basal and top-dressing methods discussed by Dayaranthna and Karunarantha [38]. In basal applications, a solid fertilizer is applied before sowing or planting, while top dressing is generally applied to already standing crops that are sown close together. Ref. [38] did not study the influence of each method; instead, these methods were employed simultaneously. Before sowing, the authors dried banana peels in sunlight for 20–25 days, crushed them to form a powder, and sieved them using a sieve with a mesh of 2 mm. Thereafter, pots were filled with 1 g of the dried powder peels and sealed. A recommended inorganic fertilizer was also added to the soil and used as a control. Two days later, two Okra seeds were sown, and the growth and yield of the plants were observed on the 2nd, 4th, 6th, and 8th weeks after planting (WAP). Other treatments, such as 1 g of pomegranate peels, 1 g of orange peels, 0.5 g of banana and pomegranate peel powders, and 0.5 g of orange and pomegranate peel powders, were also investigated. The growth and yield parameters, such as leaf area; root length; chlorophyll content; days to flowering; and the dry weight of roots, leaves, and stems, were significantly enhanced by the addition of the dried peels. Each parameter varied at different weeks, with some showing a decrease. The elemental composition of the different fertilizers used in the growth of the Okra plants was not given, including the working conditions of the fertilizer. Finding the most suitable application method would benefit farmers and agricultural scientists. A sieve was used after the peels were crushed; this stimulated an interest in the influence of the sizes of the crushed fertilizers. It is known that smaller particle sizes react faster compared to larger ones. Decreasing the sizes of the particles further would be desirable since their surface area would be increased and allow for maximum interaction with the soil. A study also showed a correlation between the particle size of BP powders and pH [76]. These researchers discovered that an increase in the particle size increases the pH of the peel powder.

In a comparative study that evaluated the efficacy of BP as a fertilizer in contrast to urea and a control that had no fertilizer applied, the growth of onion leaves and radishes and their leaf colour were monitored [66]. The method involved drying BPs in sunlight for 5–7 days and then crushing them into a powder. The findings indicated that radish seedlings treated with BPs sprouted quickly, grew rapidly, and were healthier than the control and chemical fertilizer seedlings. There was no statistical difference between the measured plant heights, meaning that the chemical fertilizers did not significantly affect the plants' height. The authors observed a colour change from pale green to dark green in the plants sprinkled with BPs and chemical fertilizer, while the control remained pale green. This observation demonstrated that BPs could be effective in improving plant health. The data from onion leaves indicated that on the first three days, the growth of the plant treated with BPs was slower compared to the other treatments. However, an increase in the growth rate was observed on the 4th day in terms of height. No colour variations were observed in any of the treatments.

A banana peel, duckweed, and eggshell composite fertilizer demonstrated the ability to increase the pH of the soil to a range suitable for growing crops [19]. Their preparation as a fertilizer included air-drying for 72 h and the further oven-drying of 200 mg of each at 45 °C. Then, they were pulverized and mixed to test their efficiency and effect on the soil through the growth of wheat in three replicates. The soil was sterilized in an oven for half an hour at 80 °C. The blended organic materials accelerated the early developmental growth of the plant compared with the control experiment.

Studies of dried banana peels have shown that several factors influence fertilizer performance. These are mainly the period of nutrient release, the medium in which the organic waste is decomposed, and the fertilizer application method. It was also noticed that BPs play a crucial role in the early developmental stages of plants.

3.1.3. Composite Banana Peel Fertilizers

As discussed in the introduction, BPs are rich in K, which is favourable for soil enrichment. However, they are deficient in other nutrients, such as P, Ca, and N, which also play a crucial role in plant growth. Using this organic waste as a standalone fertilizer can significantly limit plant growth emanating from deficiencies in soil nutrients. This has led to further research into developing composite fertilizers from other organic waste combined with BPs. Such waste should be organic and endow the BPs with nutrients they lack. It can include wastes such as eggshells, orange peels, wood ash, tangerine, and pomegranate peels, to name a few. Studies presenting these types of composite waste materials, as well as their elemental composition, plant height, and other parameters, are summarized in Table 5.

Dried BPs + pomegranate peels in one pot and orange peels + BP powders in another pot, in equal proportions (0.5 g each), were used to study the effects of composite peels on the growth and yield of Okra over eight weeks [38]. The results showed that the difference in plant height between the two treatments was insignificant. However, there was a significant difference in the measured leaf area and root length between the two composite organic fertilizers. The authors found that the orange peels added to BPs enhanced the growth and yield parameters more than the pomegranate peels added to BPs. Applying these organic fertilizers at both basal and topdressing times significantly contributed to the increase in the growth and yield parameters.

The performance of a composite of banana and orange peels has been contrasted with moringa *oliefera* extracts and NPK fertilizer [77]. The study proved that BPs combined with orange peels have great potential as a fertilizer for the enhanced growth and yield of *Solanum scabrum* Mill. The methodology involved sun-drying, powdering, and sieving the peels individually. A mixed powder containing 40 g of each dried peel was used throughout their investigation. The fruit peel waste was applied every two weeks at a rate of 200 kg/ha at the base of the plants, with daily irrigation. The authors observed that the number of leaves on the plants was more significantly enhanced by the fruit peels than the NPK (20:10:10) fertilizer and *Moringa* treatments.

Furthermore, a higher shoot height was obtained from the plants treated with the blended peels, as shown in Table 5. The authors attribute this to the high contents of potassium and calcium found in banana and orange peels, which promote the movement of water and nutrients. The other plant growth parameters that were investigated were the root length, leaf area, and plant freshness. In some parameters, such as the plant's fresh weight, the NPK fertilizer performed better than the fruit peels because of the high moisture content in NPK-treated plants. However, compared with the parameters of the control plants, such as the number of leaves, leaf size, and total leaf area, the fruit peels' performance soared due to the presence of phosphorus [77]. A composite of the *Moringa* leaves and banana peels would have also generated valuable information in this study.

Table 5. Studies of the use of composites containing banana peels as fertilizers.

Test Crop	Composite Material	Elemental Analysis	Working Conditions	Plant Height	Experiment Duration	Ref.
Okra	Pomegranate and orange peels	-	-	60 cm	8 weeks	[38]
Solanum scabrum Mill	Orange peels	-	-	58.84 cm	5 weeks	[78]

Table 5. *Cont.*

Test Crop	Composite Material	Elemental Analysis	Working Conditions	Plant Height	Experiment Duration	Ref.
Chickpea	Orange peels	Soil: N = 0.4% P = 118 ppm K = 45 ppm Ca = 240 ppm	Soil: pH = 7.24 EC = 0.58 dS/m Soil Moisture = 3.1% Organic matter = 0.91%	Powder: 4 g = 45.5 cm Powder extract: 12 g = 47.83 cm Foliar application: 4 g = 51.33 cm	45 days	[79]
Mustard Looseleaf	Okara	-	-	15 cm	10 weeks	[80]
Eggplants	KCl	-	-	46.23 cm	10 weeks	[81]
Ethiopian lettuce	Coffee grounds	N = 3.25% P = 2.51% K = 3.74%	Composite pH = 7 EC = 1.10 dS/m	-	-	[82]
Wheat	Eggshell Duckweed	-	Soil pH = 5.7 Composite + soil pH = 6.9	-	90 days	[19]
Black Gram Seeds	Sugar powder Curd	N = 1.225% %K = 3.225	Soil pH = 7.4 Moisture content = 30 *w*/*w*%	-	-	[83]

In another study, an orange and banana peel fertilizer was utilized to investigate the yield and growth of a leguminous crop called chickpea (*Cicer areitinum* L.) [78]. In a greenhouse, the authors applied the peels at different doses (0, 4, 8, and 12 g/pot) and in different forms (powder, foliar spray, and powder extract). Firstly, the peels were cut into small pieces, dried in the sunlight for 20 days, sieved, and stored at room temperature. For the powder method, the fruit peel composite was applied to the pots and mixed with the soil, forming a pH of 7.24. The powder extract was prepared by dissolving 1 g of the composite fertilizer in 100 mL of deionized water and stirring for 3 days using a magnetic stirrer. It was also used as a foliar spray, whereby a liquid fertilizer was applied by spraying it onto the plant leaves as opposed to the soil [84,85].

For the plant growth phase, three seeds were planted, which were later thinned into one plant. Urea containing 46.6% N and 45% P was added as a solution at a rate of 10 kg.donm^{-1} at the beginning of planting. The results showed that different fertilizer application methods influence the growth of plants when applied at the same dosage. For instance, at a dose of 4 g/pot, the foliar spray method gave a plant height that was similar to the other methods (Table 5). The performance of the foliar spray method was consistent with the number of branches at that same dose for different treatments. A dose of 8 g via foliar spray yielded a higher number of pods, and a 4 g dosage increased the dry weight of 100 seeds relative to the powder method and compared to their controls. The importance of the method of application was demonstrated in this study, and the impact it has on the growth and yield of plants was revealed. Urea applied at the beginning of planting combined with the foliar spray method proved to be most efficient. A similar study using a different crop could be conducted to determine whether the results obtained using this method are consistent.

Banana peels in the soil enhance the nutrients essential for plant growth, especially potassium. This was observed in a study by Nossier [79], who studied the effect of dried banana and orange peels on the growth and quality of tomatoes by comparing the availability of potassium (K) and nitrogen (N) in organic and inorganic fertilizers in two experiments, i.e., laboratory incubation and a field experiment, respectively. The incubation experiments were conducted with a mix of 300 g of soil, 40 g of compost, and 40 g and 20 g of composite peel fertilizer. For the incubation experiment, the soil was treated with animal waste compost (80 kg/32 m^2) and superphosphate fertilizers (16 kg/32 m^2) before planting the tomato seedlings. It was divided into four lines: the first and second lines were treated with mineral fertilizers and the named control. The third and fourth lines were treated with composite organic fertilizer. Samples from each mixture were taken at different intervals (in weeks) for analysis. The incubation experiment displayed a decrease in the soil's nitrogen and potassium percentage as time progressed. This observation was due to microorganisms, as revealed when residues of the fertilizers were analyzed. In the field experiment, a soil analysis revealed an insignificant increase in the ratio of N and K in the soil treated with the blended peels compared with the control-treated soil. An increase was observed in the floral growth stage for all nutrients. In the vegetative growth phase, an increase in NPK took place compared to in the control. The differences in the nutrient content (NPK) of the tomato fruit were insignificant. The obtained amounts of N, P, and K are shown in Table 5, including the soil, which had high K levels. The elemental analysis of the composite organic fertilizer would be beneficial in knowing its composition when the peels are combined.

Generally, only the NPK and other minor nutrients are determined in organic fertilizers, as seen in previous studies [64,65]. Different properties and features like porosity, particle size, moisture, and chemical bonds remain unknown. Such features are crucial and influence the performance of the organic fertilizer and, ultimately, the growth and yield of the plants.

The importance of characterizing the composite peels to identify specific features and their properties, such as the types of bonds present and porosity, was highlighted by Lai et al. [79]. These authors tested the performance of a mixture of Okara and BPs on *Mustard Looseleaf* plants. Different ratios of Okara/BPs with a total mass of 50 g were evenly mixed and dried in an oven at 100 °C for 4 h. The soil was treated with 15 g of the composite fertilizer, and the plant's growth was monitored over 10 weeks. A strong O-H stretch at 3300 cm^{-1} was detected from both the Okara and banana peels. The methyl ester C-H stretch was also detected in the BPs. Scanning electron microscopy images showed fewer pores and an improved surface morphology for the 40:10 Okara/BP composite compared with other ratios. The authors found that the presence of Okara improved the microstructure of the BPs due to the high contents of lactic acid and polysaccharides within Okara, which acted as an adhesive agent, reducing pore surfaces within the Okara/BP organic fertilizer. The best growth was obtained from a 40:10 ratio of Okara/BP and the least growth of *Mustard Looseleaf* was observed with a 10:40 ratio of Okara/BP. The authors attributed this to the high amount of Okara and low BP allowing for the complete formation of non-covalent bonds within the matrix. They further mentioned that hydroxy groups could be bonded, thus reducing the water intake of the fertilizer and forming of the nutritional content of the fertilizer due to dilution. A 40:10 Okara/BP ratio was best suited for the growth of *Mustard Looseleaf* plants, with a plant height of 15 cm and leaf size of 31.80 cm^2 seen at week 10. While these composite organic fertilizers were characterized using Fourier transform infrared spectroscopy and scanning electron microscopy, their nutrient composition and pH remain unknown, and how these might have influenced the plant's growth is unknown.

3.1.4. Liquid-Based Banana Fertilizers

Employing eggplants (*Solanum melongena* L.), Hariyono et al. [81] investigated the effectiveness of liquid-based BPs and inorganic fertilizers as a source of potassium for the growth and yield of crops. Experiments were conducted with a BP liquid fertilizer only, with different concentrations of a BP organic fertilizer and KCl fertilizer to establish the right balance between the two, as well as one with KCl alone. The preparation method of the liquid fertilizer was not described in this study. The highest plant height obtained was 46.33 cm from 100% KCl, followed by 46.23 cm for that treated with the 20% BP and 80% KCl mixture, which is a non-significant difference (Table 5). Other growth parameters, such as plant height and leaf number, showed insignificant differences between the treatments. However, a sharp increase in leaf number and plant height occurred in the fourth week after applying the organic fertilizer. This can be explained by the fact that the fertilizer was given ample time release its nutrients. The yield parameters chosen for observation, such as the fruit diameter, showed non-significant differences between the given treatments.

An exception was observed for the fruit weight (g), where a significant increase in weight was found in the plants treated with 100% BP liquid fertilizer. The variation in fruit length and diameter at an α level of 5% showed no significant difference between the treatments, while the largest fruit diameter was exhibited in 100% BP. The study demonstrated that BPs have a similar efficacy to KCl inorganic fertilizers in the growth and yield of eggplants. BPs can be used as a source of potassium and replace inorganic KCl fertilizer. The best ratio of BP: KCl fertilizer was not given.

Bedhasa et al. [82] prepared a liquid composite fertilizer of coffee grounds and BPs through aerobic fermentation. Three kilogrammes of each starting component were placed in a pot and covered with cotton wool for 60 days at ambient temperature. They were sprayed with diluted activated microbiological formulations that included yeast and lactic bacteria. Six litres were formed from the 6 kg of substrate used. The quality of the liquid fertilizer was determined using its pH, electrical conductivity, and carbon: nitrogen (C:N) ratio. The findings revealed that the liquid composite fertilizer met the basic requirements in terms of its plant micronutrients. Micronutrients such as Mg, Ca, and Na were also detected. The organic fertilizer was evaluated on Ethiopian lettuce in a completely randomized design, with two replicates, under greenhouse conditions. Four seeds were placed in each pot and 500 mL of liquid organic fertilizer was added during planting. The control was compost tea waste, and only 500 mL of water was added. The crops were first irrigated with water only and this was subsequently followed by liquid fertilizer on the experimental crops. The authors discovered that their bio-organic liquid fertilizers achieved better results than the control, meaning that the measured parameters, such as biomass weight per plant and days to maturity, were significant compared to the control treatments. The exception was the number of leaves per plant. While the study makes use of organic materials to synthesize the fertilizer, a significant amount of data on crop growth and yield was not collected. These data include the diameter, leaf area, root length, colour, and dry weight of the plants. Due to its high dietary fiber, which assists with digestion, it would be desirable to determine some of the chemical properties of the plant. Additionally, characterizing the soil before and after harvesting the crop is crucial as it assists in rationalizing the obtained results and in determining the amount of fertilizer required by the soil.

The development of new methods for the synthesis of organic fertilizers is essential to enhance the properties of ordinary fertilizers. Researchers have developed a novel approach to improve the growth of fenugreek and tomato crops using an extract of BPs converted to the nanoscale [65]. Initially, the peels were mechanically crushed in a blender with tap water. This viscous liquid was stirred with potassium hydroxide to obtain a homogenous mixture and then subjected to boiling for 30 min with stirring. The slurry was cooled to room temperature and filtered. The clear filtrate was heated to 70 °C with stirring at 300 rpm. Then, 5% solutions of both urea and citric acid were added until a pH of 5 was obtained, and the slurry was subsequently dried at 105 °C and ground to yield a powder. This formed a nano-powder that was applied in different doses (4, 8, 12, 16 mL/L) to soil containing the two test crops. The data in this study indicated that an increase in the dosage increases the germinating percentage of both crops. The increase was due to the high content of amino acids (L-tryptophan) and potassium. Although the research successfully explored the effect of the nano-fertilizer on the germination rate, giving impressive results, a comprehensive study of other plant growth parameters such as plant height and yield would give an in-depth understanding of the impact of the prepared nano-fertilizer on the growing of fenugreek and tomato crops.

A liquid fertilizer can be prepared by the fermentation of banana peels alone or when blended with other materials. In one example, shredded Indian banana peels (0.5 kg), 15 pieces of sugar powder, and 30 g of freshly prepared curd were fermented in tap water for 15 days [83]. Thirty-six seeds of black gram were planted and irrigated with water comprising 350 mg/L of total suspended solids and various doses of the bio-fertilizer (5, 10, 15, and 20 mL/L). A week after the seeds were planted, germination data were collected, and it was found that they increased with the increase in the dosage of the composite fertilizer. The authors attributed this observation to the increased concentration of K in the peels; however, it can also be added that fermenting the blended mixture for 15 days allowed nutrients to be released. The application technique and materials used to formulate a composite fertilizer greatly impact its characteristics and performance. A formulation comprising banana peel, bean sprouts, and eggshells was found to be outshined by one containing banana humps, onion peels, bean sprouts, and moringa leaves, which displayed an improved magnesium and chlorophyll content [86]. This could be attributed to the presence of moringa in the second formulation, as it is rich in magnesium [87]. Thus, it is important to optimize parameters such as the concentration of the components that make up the composite fertilizer, as well as its application rate. The same fertilizer can yield different results at different rates. This was observed in the study by Howeidi et al. [88], where 40 mL/L of BP-based fertilized resulted showed outstanding results for plant height, the number of leaves, and percentage of dry matter in the vegetables and roots, while 20 mL/L excelled in improving the relative chlorophyll content in the leaves, average root weight, and size and yield. Other studies in this area only focused on evaluating banana peels individually or as part of a composite fertilizer by determining their chemical contents [86,89].

3.2. Banana Peel Ashes and Biochar

3.2.1. Banana Peel Ashes

Ashes are solid, powdery materials that generally remain after the combustion of biomass (wood, leaves, cellulose, lignin, manure, forest, and agricultural waste) in the presence of oxygen. Wood ash is the most common type of ash, and it results from burning wood for heat and fuel. Like any waste material, ashes are discarded and not converted into valuable products. However, studies [90–94] have shown the occurrence of some beneficial minerals for soil enrichment in agriculture, such as calcium (Ca) and potassium (K), in organic ash. Their value contributes towards alleviating environmental pollution, the costs associated with its disposal, and opening up waste landfill sites. Another type of ash, from combusted BPs, has been shown to be interesting due to its high potassium content, which can be converted to commercial products such as fertilizers.

The peels are combusted to obtain ashes that can be applied as a fertilizer, as demonstrated by Franck et al. [95], who investigated the growth and ripening of red onions (red creole) using potassium extracted from BP ashes. The plant of interest was chosen due to its high potassium needs. The peels were sun-dried for 7 days and then calcined at a temperature of 350 °C in a muffle kiln for 8 h, forming ashes. From 100 kg of BPs, 3.9 kg (3.9%) of ashes were generated. However, the composition of the ashes was not determined to compare the potassium content before and after calcination. The obtained ash was dissolved in distilled water at a 0.25 water–ash ratio to leach its potassium and the mixture was stirred for 24 h. The mixture was centrifuged at 4000 rpm for 10 min to form white crystals (86% potash). The red creole was transplanted after spending 60 days in a nursery. Urea was applied at 0 and 200 kg, and NPK at 600 kg, including in combination with K fertilizers (Table 6), after 20 days of transplanting, and observation began after 15 days of the first dosage. The K fertilizer was applied at 0, 150, and 200 kg, and the authors realized that the results of the growth parameters of the red onion were similar to the untreated control samples. However, the yield parameters showed a significant difference from those of the control. This was because the fertilizer works more efficiently on the underground part of the plant and aids root development compared to aerial development. The two doses of 150 and 200 kg gave similar results due to the availability of exchangeable K in the soil solution. The authors further stipulated that the results of the 200 kg were almost similar to NPK (10:20:10) and showed that this ash-based fertilizer is suitable for a specific type of soil (drill liter). This means other soil types would be less suitable for this ash-based fertilizer. It was recommended that the fertilizer be combined with nitrogen- and phosphorus-rich fertilizers.

Table 6 demonstrates the effects of different amounts (kg) of NPK, urea, and K fertilizer and their mixtures on the size and leaf number of onion at 65 days (T65), as well as its weight. The onions were grown in NPK (600 kg) fertilizer and those treated with combinations of NPK (600 kg) + urea (200 kg), and NPK (600 kg) + K (200 kg) had similar sizes. The NPK (600) +K (150 kg) mixture gave the highest number of leaves and plant weight of the onions. This observation can be attributed to the addition of nitrogen and phosphorus to the soil. The authors reported that a high presence of nitrogen in the soil favours the aerial development of a growing plant through photosynthesis. In general, nitrogen plays a significant role in plant growth since it regulates the biochemical and physiological functions of plants. It is the key element that produces the greatest crop response in plants, giving plants their green colour and promoting rapid vegetative growth. A nitrogen deficiency in soil is identifiable by the yellowing of plant leaves. However, the excessive application of nitrogen reduces crop yield and adversely affects crop quality. Phosphorus promotes seed germination and viability, increases plant root length, and promotes flowering [38]. It also stimulates plant cell division and enlarges cell tissue [81]. As a result, the initial growth of phosphorus-deficient plants is gradual [62], and their overall growth is with fewer leaves [77].

Table 6. Effect of banana peel ashes and inorganic fertilizers on plant height and the number of leaves seen at 65 days [95].

Parameter		Plant Size at Day T65	Number of Leaves	Plant Weight
NPK (600 kg)		52	8.3	73.4
Urea (200 kg)		49.4	7.4	60.5
K fertilizer	150 kg	42.4	6.5	55.1
	200 kg	45.9	7.7	57.3
NPK (600)	K (150 kg)	48.3	16.6	83.6
	K (200 kg)	52	9.46	68.2
NPK (600 kg) + Urea (200 kg)		52.23	8	69.5
K (150 kg) + Urea (200 kg)		41.7	5.5	46.7
K (200 kg) + Urea (200 kg)		49.5	8	65.9

3.2.2. Banana Peel Biochar

Biochar is a fine, carbon-rich, organic material synthesized through the pyrolysis of biomass [96]. In pyrolysis, biomass decomposes at temperatures greater than 400 °C in limited or in the absence of oxygen. A mixture of gas (syngas), liquid (bio-oil), and solid (biochar) products are formed [97]. To favour biochar formation, biomass is normally pyrolyzed slowly, at a heating rate of 5–20 °C per minute and with higher residence times [98–100]. The properties of biochar are directly impacted by its pyrolysis conditions, such as the type of feedstock material (size and shape) used, temperature, reactor shape and type, heating rate, residence time, and chemical activation [101]. These also affect its applications.

Table 7 presents the synthesis conditions of BP biochar from the different studies reviewed in this work. Long residence times, high catalyst masses, and low temperatures were found to give better yields.

Generally, biochar exhibits high biodegradability, high contents of total carbon and organic carbon, and optimal concentrations of micro- and macro elements (potassium, sodium, magnesium, calcium, copper, zinc, iron, etc.). Properties such as these have given it applications related to the various fields of agriculture, and specifically to soil health. Biochar from wheat has been reported to increase soil permeability by 35.4–49.5%, decrease bulk density by 5.5–11.6% in clay loamy soil using saline irrigation water, and further increase the yield of wheat grain [102]. Due to its porous nature, it is efficacious at retaining water and water-soluble nutrients [102]. It can effectively reduce soil emissions of CO_2 emanating from the excessive usage of chemical fertilizers [103–105]. Several studies reported an improvement in soil microbial activity [106] and soil properties such as pore size distribution, soil organic carbon [107], pH [108], soil structure [109], and cation exchange capacity (CEC) [110] upon its application. Additionally, it can reduce nutrient leaching, thus reducing soil erosion, enhancing nutrient availability, and protecting soil from fungal pathogens [100,106,110]. However, the biological and physicochemical characteristics of soil influence the outcome of soil health and crop growth. For example, a review by Vijay et al. [111] observed a trend that biochar application is more beneficial for soils in tropical regions than in other regions. Some research has been conducted on biochar additions to soil using different biomass sources such as grass, wheat straw, corn, rice husk, and other agricultural residues [112]. There are some studies on BP biochar utilized to amend soil [113], but they are limited.

The biomass feed for pyrolysis must be environmentally friendly and considered safe for production. This is usually determined by a series of analyses, namely ultimate and proximate analyses. An ultimate analysis measures the C, H, O, N, and S concentrations in the pyrolysis feed in terms of percentages. A proximate analysis measures ash levels, fixed carbon, volatile matter, and moisture content. Usually, the calorific value or heating value is also investigated.

Table 7. Synthesis parameters and yield of biochars from banana peels.

Ref.	Reactor Type	Feed Mass (g)	Temp (°C)	Heating Rate (°C/min)	Residence Time (min)	Biochar Yield	O/C Ratio
[113]	-	-	400	-	60	-	-
[114]	Batch Reactor	10.10	450	10	67.50	35.64%	-

Banana peels were found to be a suitable feedstock for pyrolysis by Kabenge et al. [115]. Their proximate analysis tests showed its low moisture content, indicating that less energy would be required to evaporate the water contained in the biomass feed. The authors found an ash content of ~9% ideal since high-ash biomasses are poor energy converters and can cause corrosion. A high percentage of volatile matter indicates a high susceptibility to thermal degradation, and the BPs had one of 88.02%. For their ultimate analysis, low sulphur and nitrogen concentrations were detected and showed that minimal nitrogen oxide and sulphur oxide gasses were emitted.

A study was conducted by Islam et al. [113] on the conversion of BP waste to biochar as a source of plant nutrients. The transformation to biochar took place in a significantly low-oxygen-containing decomposer container that was heated for 2 h at a temperature of 400 °C. The charred peels were ground and sieved to evaluate the growth of *Ipomoea aquatica*. Analysis of the biochar revealed high K (42.55%), Na (14.19%), and Ca (11.53%) contents, and a low nitrogen content (0.95%). Concentrations of K and P were also found in the soil (Table 8). One kg of soil was mixed in a 2 L pot with varying amounts of charred peel powder (1, 2, and 3% w/w). The plants were thinned when they had grown and harvested after 42 days. The BP biochar had a minimal effect on plant height and was not statistically significant from the control, meaning that the plant height was higher in the control. The plants' leaf number, fresh weight, and dry weight in the 2 and 3% treatments were increased compared to the 1% and control. The results obtained by Islam et al. [113] are consistent with the work of Helliwell [116] and Tian et al. [117], where a biochar addition was found to be ineffective at promoting plant growth. However, applying the biochar at higher percentages (>3%) was found to have a significant effect on the growth of plants. This can also explain the insignificant differences in the results between the control and treated plants obtained by Islam et al. [113]. Banana peel biochar has been found to suppress chromium toxicity, promote iron uptake, and improve plant growth parameters compared to a control [118]. However, researchers have discovered that the foliar application of iron alone yielded even better results compared to a BP biochar. The effect of using composite biochar from different biomass sources could be studied. As previously mentioned, the process of pyrolysis used to synthesize biochar is controlled by various parameters. The synthesis conditions can be optimized to favour biochar formation in high yields. Researchers may choose literature-based values within a certain range for each parameter to investigate their influence on the formation of biochar and its properties.

The response of these values can either be investigated manually or using several software tools such as Design Expert and Minitab [119]. When manually investigated, other parameters are held constant while one is investigated. When utilizing software, various sequential processes such as response surface methodology (RSM), etc., exist and are employed to determine the influence of independent variables on one or more responses [120]. In this way, the optimum conditions for biochar synthesis are determined.

Using the central composite design (CCD) from RSM, Omulo et al. [114] demonstrated the optimization of biochar production from BPs. Slow pyrolysis took place in a batch reactor at a heating rate of 10 °C/min. The pyrolysis conditions were a temperature of 350–550 °C, a sample mass of 200–800 g, and a residence time of 45–90 min. Using these conditions, 20 experimental runs were conducted. The highest yield of biochar was obtained, 30.10%, from the synthesis conditions displayed in Table 7. Vinegar, tar, and non-condensable gas were also produced.

Table 8. Summary of studies of banana peels transformed into biochar for fertilizer applications.

Test Crop	Elemental Composition	Working Conditions	Experimental Duration	Plant Height	Ref.
Ipomoea aquatica	N = 0.95% K = 42.55% Na = 14.19% Ca = 11.53%	Soil: pH = 7.8 Total N = 0.09 P = 21.36 µg/g K = 0.03 µg/g EC = 1.29 dS/m	42 days	32 cm	[113]
-	C = 35.65% H = 6.19% N = 1.94% O = 45.94	-	-	-	[116]

The quality of the BP biochar was not investigated in that study. Although it is widely known that biochar contains aromatic functional groups, it would be beneficial to determine their presence and quantity in banana peel-based biochar. Other properties of the biochar, such as porosity, that affect its performance as fertilizer are also desirable to know. Furthermore, the authors did not test the effect of the BP-based biochar on soil health and plant growth and yield..

4. Comparison of Different Methods for Preparing Banana Peel-Based Fertilizers

Figure 3 depicts (in percentages) each method used in the studies reviewed. It has been noticed that composite peels are the preferred method, followed by homogenous dry and wet peels. This could be due to the economical simplicity of the synthesis method, which generally requires peels, heat (sun or hot air), and a pestle and mortar. In addition, the composite fertilizer has the combined properties of the individual peels. Three types of composite peels were discovered in this work: dry or powder, ash, and liquid composite peels.

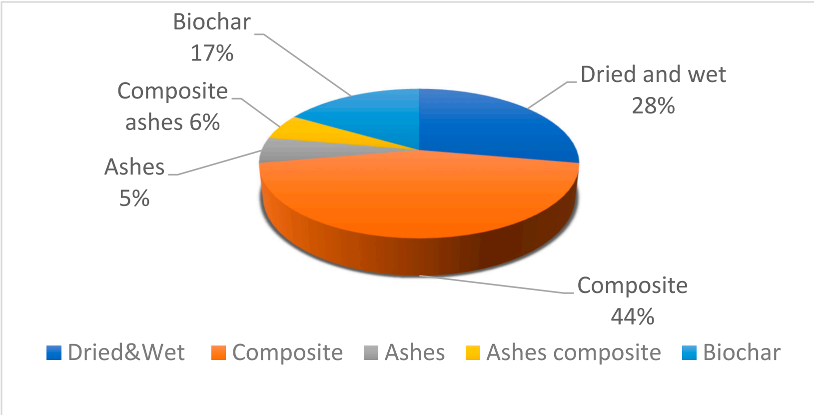

Figure 3. Various methods for preparing banana peel-based fertilizers.

As seen in Figure 4, 60% of studies applied the composite peels in dry form. Composite fertilizers in a liquid state follow at 30%; this is also a facile synthesis technique, and distilled water is generally used to extract the nutrients. What can be noted with the liquid composite is the generation of two products, i.e., the leachate liquid and a residual powder. The extract can be applied as a foliar spray at different plant leaf growth stages, as well as absorbed by the fertilizer. The residual materials can be applied to the plants before planting them in the soil and at different growth stages.

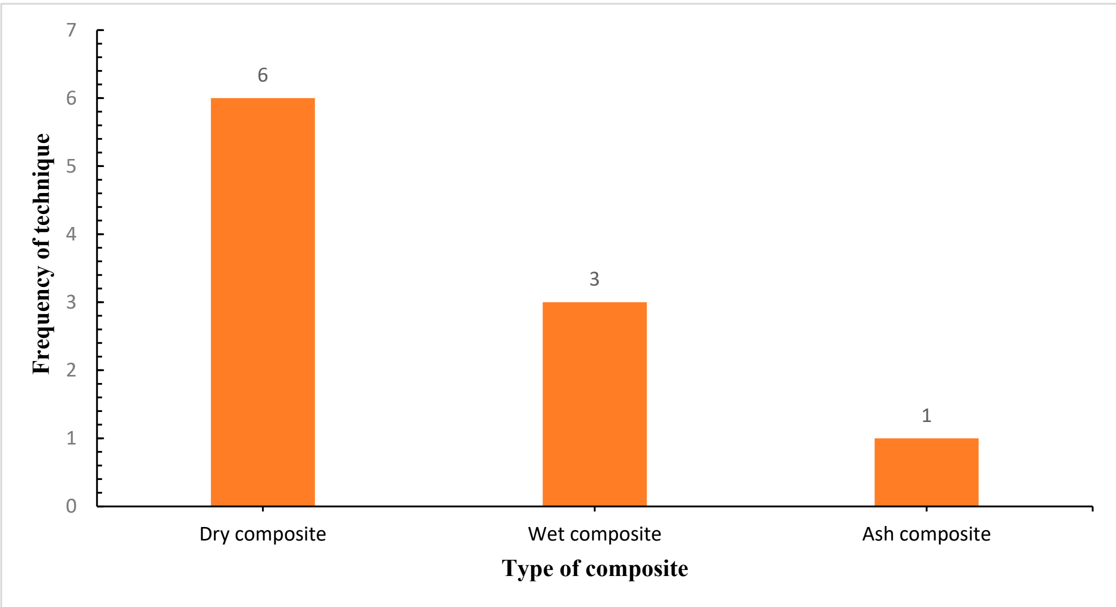

Figure 4. Types of identified composite fertilizers and their frequency.

Biochar has some other benefits besides supplementing the soil with nutrients; a non-significant difference between the control and treated plants was observed, and root elongation was affected at higher dosages. A composite fertilizer of banana biochar impregnated or coated with other peels and/or N:P: K fertilizers could be investigated. A slow-release fertilizer could be developed, as well as its composite version, as demonstrated by Das and Ghosh [121]. The synthesis of biochar requires an external supply of energy for the pyrolysis of biomass, as well as specialized equipment. Due to this, other methods might be preferred over it. An under-researched area is the process of the gasification of BPs for fertilizer applications.

Research efforts could be made to synthesize biochar from gasification and test this biochar as a fertilizer. Only one study [94] of ash-based fertilizers prepared from banana peels was conducted, to the authors' knowledge. A significantly small amount of ash (3.9 kg) was obtained from BPs (100 kg), which makes them an unfavourable organic fertilizer. The yield was also low compared with biochar yields [114]. The production of BP ashes could be optimized to determine the optimum synthesis conditions and find the best yield.

The application method used for the organic fertilizers was observed to be significant and influential to plant growth. These include basal, top-dressing, and foliar spray applications. Based on their influence, using the basal and top-dressing methods simultaneously is recommended, and, based on Figure 3, dry composite banana peels are the best method for preparing BP fertilizer. The choice of composite material can be based on the needs of the plant.

Most studies reviewed overlooked essential variables such as experimental conditions, including the soil type, soil pH, germination rate, nutrient composition of the BP fertilizer, and electrical conductivity. Furthermore, banana peels from different geographical areas and varieties exhibit variations in their chemical and physical properties. Therefore, it is crucial for reports to specify the banana peel's variety, where possible, and to detail the physicochemical properties of the banana peel used. More field experiments evaluating the yield quality are necessary to understand the effectiveness of BP fertilizers comprehensively. Using the most effective methods, the pilot-scale production and application of BP fertilizer could provide valuable insights into its scalability, practicality, and future prospects. Additionally, a thorough characterization of soil types, electrical conductivity, pH, and nutrient content should be conducted to fully understand BP's potential as a fertilizer.

5. Conclusions and Future Prospects

The studies reviewed in this work included different preparation methods for organic fertilizers, namely dried peels, composite peels, ashes, and biochar. It was observed that banana peel-based fertilizers improved the growth and yield of the test crops. It was discovered that the most preferred method in the studies was the use of composite peels, namely orange and banana peels. Studies focusing on the mechanisms by which BPs enhance plant growth and the characterization of the soil and BPs used could be conducted to better understand the influence of these methods on plant growth. The mechanism at work can be assessed through active measures of plant growth, which are achieved through measuring overall photosynthesis and gas exchange parameters. Photosynthesis reports about the efficacy of making carbohydrates, which contribute directly towards enabling all the metabolic processes taking place within a plant, while gas exchange reveals stomatal regulation and hence the rate and efficacy at which a plant fixes carbon dioxide to synthesize the assimilates necessary for growth. It further reports the potential of BPs to improve water use efficiency. The integration of photosynthesis and gas exchange parameters also demonstrate the efficacy of BPs in inducing abiotic stress tolerance. Moreover, the findings reported in this study are on the effect of BPs on growth, yield, and macronutrients (particularly NPK); however, consumers are becoming increasingly concerned about quality. Therefore, the effect of using banana peel-based fertilizers on micronutrients, vitamins, and secondary metabolites still needs to be explored. This is necessary because these are the quality attributes of products that humans consume and serve as essential components of the human diet. Characterization of the soil would assist in identifying the physical, microbiological, and chemical properties of the soil and banana peels. Information such as the nutrients available and their levels, the organic matter content, water holding capacity, porosity, particle size, pH, CO_2 release, and functional groups of BPs can aid in deducing how the application of BPs aids in improving soil structure.

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Abbreviations

BPs	Banana peels
NPK	Nitrogen, phosphorous, potassium
Zn	Zinc
K	Potassium
NMR	Nuclear Magnetic Resonance
IR	Infrared spectroscopy
FTIR	Fourier transform infrared spectroscopy

WAP	Week after planting
P	Phosphorous
Ca	Calcium
N	Nitrogen
KCl	Potassium chloride
C:N	Carbon–nitrogen
Mg	Magnesium
CEC	Cation exchange capacity
C	Carbon
H	Hydrogen
O	Oxygen
S	Sulphur
CCD	Central composite design
EDX	Energy Dispersive X-ray Spectroscopy
O/C	Oxygen/carbon
CRD	Completely randomized design
CO_2	Carbon dioxide
DW	Dry weight
EC	Electrical conductivity
Fe	Iron
Mn	Manganese
RSM	Response surface methodology

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