



REVIEW

Banana Peel-Vermicompost Nanofertilizers for Improving Soil Fertility and Maize Production in Kenyan Smallholder Farming Systems

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ABSTRACT: Soil degradation and low nutrient availability constrain agricultural productivity among small-holder farmers in Sub-Saharan Africa. In Kenya, these challenges are compounded by limited access to fertilizers, inefficient nutrient use, climate variability, and declining soil organic matter. Although synthetic fertilizers can increase crop yields, their high cost and nutrient losses through leaching and volatilization can reduce nutrient-use efficiency and increase environmental risks. Vermicompost can improve soil organic matter, nutrient availability, and biological activity, but its relatively slow nutrient release may limit nutrient supply during critical crop growth stages. This review examines the potential of banana peel-vermicompost-based nanofertilizers to improve soil fertility and maize production in Kenyan smallholder farming systems. The reviewed evidence indicates that banana peel-vermicompost-based nanofertilizers can improve plant growth, soil organic matter, microbial activity, and nutrient availability. Reported studies show increases in maize plant height and root biomass of 26.3% and 37.8%, respectively, and increases in organic matter and microbial populations of 19.5% and 24.8%. Some studies also report yield improvements following the use of banana peel-derived or nano-enabled amendments. However, a higher percentage of the available evidence comes from greenhouse, pot, or short-term experiments, while multi-season field evidence under Kenyan smallholder conditions remains limited. Banana peel-vermicompost-based nanofertilizers therefore represent a potential circular approach for recovering nutrients from organic waste and improving soil fertility. However, their application in Kenya requires field-scale validation, assessment of nanomaterial safety, evaluation of production and application costs, and farmer training and extension support.

KEYWORDS: Circular bioeconomy; banana peel-vermicompost; soil fertility; nanotechnology; nutrient use efficiency

1 Introduction

Soil degradation and declining soil fertility are major constraints to agricultural productivity in many tropical and subtropical regions, including Kenya [1,2]. In smallholder farming systems, these problems are associated with continuous cultivation, monocropping, soil erosion, loss of organic matter, and inefficient use of external inputs [3]. Declining soil fertility reduces nutrient availability and can limit crop productivity, particularly where farmers have limited access to improved inputs and soil-management technologies.

Synthetic fertilizers remain an important source of nutrients for crop production because they provide readily available nitrogen (N), phosphorus (P), and potassium (K). However, many commonly used fertilizer formulations supply these nutrients in fixed ratios and may provide limited amounts of secondary nutrients such as sulfur (S), calcium (Ca), and magnesium (Mg), as well as micronutrients such as boron (B), iron (Fe), and zinc (Zn) [4]. In addition, fertilizer losses through leaching, volatilization, and other pathways can reduce nutrient-use efficiency and increase environmental risks. High fertilizer prices and limitations in distribution and market access further restrict their use by smallholder farmers.

Organic amendments, including animal manure, compost, crop residues, and vermicompost, provide an alternative or complementary approach to improving soil fertility [5]. These materials can contribute organic matter and nutrients while improving soil structure, water retention, and biological activity. Vermicomposting is of particular interest because earthworms and associated microorganisms transform organic residues into a stabilized material containing nutrients, humic substances, and beneficial microorganisms [5]. However, the nutrient composition of vermicompost varies with the feedstock and production process, and its nutrients may be released more slowly than those supplied by soluble fertilizers. The relatively large quantities required for field application can also increase transport and handling costs.

Banana production generates substantial quantities of peel, pseudostem, and other residues. Banana peels contain nutrients, particularly K, and can therefore be recovered and processed into organic amendments [6]. Their use in composting and vermicomposting provides an opportunity to convert an agricultural waste stream into a soil amendment while reducing waste accumulation. However, the potential value of banana peel-derived amendments depends on their chemical composition, processing method, nutrient release characteristics, and performance under field conditions.

Nanotechnology has recently attracted interest in agriculture because nanoscale materials can modify nutrient release, transport, and availability [7]. Nanofertilizers may be designed using nutrient-containing nanoparticles or nanocarriers that regulate nutrient release and potentially reduce nutrient losses [8]. However, the benefits of nanofertilizers depend on particle composition, size, concentration, application method, and soil and crop conditions. Concerns also remain about their effects on soil microorganisms, non-target organisms, environmental persistence, production costs, and long-term safety [9].

Combining banana peel-derived organic amendments with nanotechnology could therefore provide a means of integrating nutrient recovery with more targeted nutrient delivery. Such an approach is particularly relevant to Kenyan smallholder maize systems, where soil fertility constraints, variable rainfall, fertilizer costs, and limited access to external inputs can restrict productivity. However, the available evidence is not yet sufficient to establish whether banana peel-vermicompost nanofertilizers consistently improve maize productivity under field conditions in Kenya.

This review therefore examines the potential of banana peel-vermicompost-based nano-fertilizer for improving soil fertility and maize production in Kenyan smallholder farming systems. Specifically, the review evaluates (i) the nutrient and soil-health benefits of vermicompost and banana peel-derived amendments, (ii) the principles and potential benefits of nanofertilizers, (iii) possible approaches for integrating banana peel vermicompost with nanotechnology, and (iv) the opportunities, limitations, and research needs associated with their application in Kenya.

2 Problems in Africa's Agriculture and the Role of New Technologies

Africa's agricultural soils face a combination of physical, agronomic, environmental, and socioeconomic constraints. In warm and humid tropical regions, high rates of weathering and nutrient leaching can produce highly weathered soils with low nutrient-retention capacity, including ferrallitic soils [10]. Poor

land management can further accelerate soil compaction, aggregate breakdown, erosion and loss of topsoil and organic matter [11,12]. In drier regions, inappropriate irrigation practices can contribute to soil salinization [13]. Together, these processes reduce soil quality and constrain crop productivity over time [14].

Synthetic fertilizers provide readily available nutrients and can increase crop yields in the short term. However, their efficiency depends on application rate, soil conditions, crop demand, and management practices [15]. Excessive N application can increase nutrient losses, contribute to eutrophication, reduce soil pH, and increase greenhouse gas emissions [16]. Evidence from China, for example, shows that N and P use increased substantially over a decade, whereas cereal yields increased at a much lower rate, indicating declining input-use efficiency [17]. Similarly, excessive pesticide use can contribute to biodiversity loss, toxicity to non-target organisms, and pesticide resistance [18].

Organic amendments can partly address some of these limitations by supplying nutrients and organic matter while improving soil structure, water-holding capacity, and microbial activity [5]. Vermicompost, in particular, has been associated with improvements in soil quality and plant resilience to biotic and abiotic stresses [19]. One study reported increases in microbial biomass and soil respiration following vermicompost application compared with untreated soil. However, organic amendments have limitations. Their nutrient composition varies among feedstocks, nutrient release may be slower than crop demand during periods of rapid growth, and their relatively large application volumes can increase transport and handling costs [20]. In addition, differences in production methods, quality, and recommended application rates can affect their agronomic performance [21].

Agricultural productivity is also influenced by structural and socioeconomic constraints. Limited access to agricultural extension services, certified seed, credit, markets, and other production resources can restrict productivity independently of soil fertility [22]. Therefore, improving soil fertility alone is unlikely to resolve all constraints facing smallholder agriculture. Soil-management technologies need to be considered alongside institutional, market, and extension support.

Population growth and changing food-consumption patterns are increasing pressure on agricultural production and natural resources [23]. Global food demand is expected to increase substantially by 2050, creating pressure to increase cereal production while limiting further environmental degradation [17]. Kenya faces similar challenges. The proportion of the population experiencing moderate to severe food insecurity increased from 53% during 2014–2016 to 68.5% during 2018–2020 [24]. These pressures are further intensified by climate-related stresses, including drought, salinity, and extreme temperatures, as well as continuing soil degradation and resource depletion [25].

Such challenges have increased interest in technologies that can improve nutrient-use efficiency while maintaining or improving soil quality. Nanotechnology is one such approach because nanoscale materials can be designed to modify nutrient release, improve nutrient availability, and potentially reduce nutrient losses [7]. When combined with organic amendments and biological inputs, nanotechnology may provide a means of coordinating nutrient supply with crop demand [26]. However, neither synthetic fertilizers, organic amendments, nor nanotechnology should be considered sufficient on their own. Their effectiveness depends on how they are designed, applied, and integrated within specific soil, crop, and farming systems.

3 Vermicompost: Methodology of Preparation

Vermicomposting is a biological process (Fig. 1) in which earthworms and mesophilic microorganisms interact to transform organic wastes into a stabilized organic amendment known as vermicompost [27]. Unlike conventional thermophilic composting, vermicomposting occurs without sustained thermophilic

conditions. The combined activity of earthworms and microorganisms accelerates the decomposition and stabilization of organic matter [28].

The resulting vermicompost contains nutrients, humic substances, microorganisms, and enzymes that can contribute to nutrient cycling and soil biological activity (Table 1). Vermicomposting can also provide a means of recovering nutrients from agricultural, household, and urban organic wastes while reducing the amount of organic material disposed of through uncontrolled dumping or burning [29].

Different earthworm species are used for vermicomposting. *Eisenia fetida* is widely used because of its tolerance to a range of environmental conditions [30]. Vermicompost may contain micronutrients such as Fe, Zn, copper (Cu), manganese (Mn), and boron, together with exchangeable calcium and Mg and biologically active compounds. Compared with conventional thermophilic composting, vermicomposting can reduce N losses and produce a relatively stable amendment with a lower carbon to nitrogen (C:N) ratio [31]. Its application has been associated with improvements in soil aggregation, water-holding capacity, nutrient availability, microbial activity, and enzyme activity [32].

Application rates vary according to the feedstock, crop, soil condition, and nutrient concentration of the final product. Reported rates range from approximately 6–8 t ha⁻¹ for some vegetable crops to about 20 t ha⁻¹ for crops such as garlic [30]. These differences highlight the importance of considering the nutrient composition of vermicompost when determining application rates.

Table 1: Bacterial species identified within various earthworm guts and their associated beneficial agricultural traits for soil health and plant growth promotion [31].

Vermicompost Earthworm	Names of Bacteria	Beneficial Traits
<i>Eudrilus</i> sp.	Free nitrogen fixers; <i>Azospirillum</i> , <i>Azotobacter</i> , autotrophic <i>Nitrosomonas</i> , <i>Nitrobacter</i> , ammonifying bacteria, phosphate solubilisers, fluorescent <i>Pseudomonas</i>	Plant growth promotion by nitrification, phosphate solubilization, and plant disease suppression.
<i>Eisenia fetida</i>	Proteobacteria, Bacteroidetes, Actinobacteria, Firmicutes, Verrucomicrobia	Antifungal activity against <i>Colletotrichum coccodes</i> , <i>R. solani</i> , <i>P. ultimum</i> , <i>P. capsici</i> , and <i>Fusarium moniliforme</i>
<i>Lumbricus terrestris</i>	Fluorescent pseudomonads, filamentous actinomycetes	Suppress <i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i> , <i>F. oxysporum</i> f. sp. <i>asparagi</i> , <i>F. proliferatum</i> , and <i>Verticillium dahliae</i>
Unspecified	<i>Eiseniicola composti</i> YC06271	Antagonistic activity against <i>F. moniliforme</i>
<i>Eisenia fetida</i>	<i>Bacillus</i> spp. (<i>B. megaterium</i> , <i>B. pumilus</i> , <i>B. subtilis</i>)	Antimicrobial activity against <i>Enterococcus faecalis</i> DSM2570 and <i>Staphylococcus aureus</i> DSM 11048
<i>Aporrectodea trapezoides</i>	<i>Pseudomonas corrugata</i> 2140R	Inhibit <i>Gaeumannomyces graminis</i> var. <i>tritici</i> infestation in wheat crops
<i>Aporrectodea rosea</i> , <i>A. trapezoides</i>	<i>Rhizobium meliloti</i> L5-30R	Boost root nodulation and enhance nitrogen fixation in legume plants
<i>Microscopus dubius</i> , <i>L. terrestris</i>	<i>Bradyrhizobium japonicum</i>	Spatial distribution of nodules along soybean root systems
Unspecified	<i>Rhizobium trifolii</i>	Supporting nitrogen assimilation and vegetative growth in leguminous species
<i>Lumbricus rubellus</i>	<i>Rhizobium japonicum</i> , <i>Pseudomonas putida</i>	Stimulate overall plant growth
<i>Pheretima</i> sp.	<i>Pseudomonas oxalaticus</i>	Breakdown and degradation of oxalate compounds

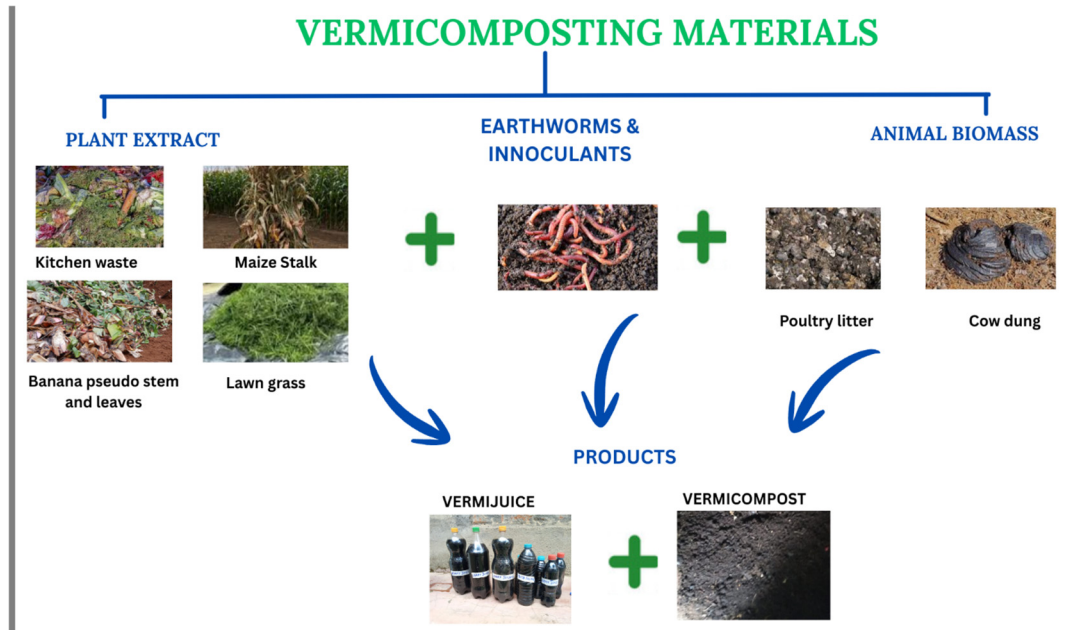


Figure 1: Comprehensive overview of raw materials utilized in the vermicomposting process, including plant extracts, animal biomass, and earthworm inoculants used to produce vermi juice and vermicompost.

Vermicomposting can be conducted using batch systems or continuous-flow systems [29]. A typical production cycle may require approximately 45–60 days, although the duration varies with the feedstock and environmental conditions [33]. Fresh organic wastes are commonly subjected to a pre-composting stage before earthworms are introduced. This stage helps reduce excessive heat and potentially harmful compounds and can improve the suitability of the material for earthworm activity [34].

The vermicomposting unit may consist of a bin, wooden structure, cement structure, or earthen bed. A layered system can include a drainage layer, fine sand, shredded plant material, and pre-composted organic waste mixed with aged animal manure [29,35]. Bulking materials can be added to improve aeration and maintain a suitable C ratio [30].

Environmental conditions strongly influence earthworm activity and decomposition. For *Eisenia fetida*, suitable conditions generally include temperatures around 20–30°C, moisture contents of approximately 60–85%, and a near-neutral pH of 6.5–7.5 [36,37]. The initial C:N ratio may range from approximately 25:1 to 30:1 and decline as decomposition progresses [34]. Small-scale systems commonly use perforated bins, whereas larger operations may use windrows or continuous-flow reactors [29,38].

At maturity, vermicompost is generally dark brown, granular, and relatively free of unpleasant odors. Watering may be stopped several days before harvesting to encourage earthworms to move downward and facilitate separation of the finished material [30,38]. The harvested vermicompost can then be dried to an appropriate moisture content, sieved to remove residual earthworms and large particles, and stored under cool and dry conditions [39].

3.1 Chemical Composition of Vermicompost

Vermicompost contains substantial macronutrients such as N, P, and K, as well as micronutrients including boron, Cu, Fe, and Zn. It may contain exchangeable calcium and Mg, humic substances, and plant-growth promoting compounds [29,40].

For example, vermicompost produced from municipal waste in the Nigerian Sahel contained 1.60% total N, 0.47 mg kg⁻¹ available P, 720 mg kg⁻¹ exchangeable K, and 2.80% organic carbon (OC), with a pH of 6.8 [41]. This example illustrates the variation in nutrient composition among vermicompost produced from different feedstocks.

Vermicomposted farmyard manure (FYM) has also been reported to contain higher concentrations of N, P, K, and selected micronutrients than untreated farmyard manure [40]. The differences may reflect greater organic-matter stabilization during vermicomposting. Humic substances and other biologically active compounds in vermicompost may further influence nutrient availability and plant nutrient uptake [42].

3.2 *Banana (Musa acuminata) Vermicompost*

Banana (*Musa* spp.) is widely cultivated in tropical and subtropical regions, including Brazil, China, Ecuador, Indonesia, India and Kenya. In Kenya, banana production is concentrated in several regions, including Central, Eastern, Western, and parts of the Rift Valley [43,44]. Commonly cultivated varieties include Cavendish, Apple Banana (Manzano), Plantain, Red Banana, and Lady Finger [45].

Banana production and consumption generate substantial quantities of organic residues, including peels, leaves, and pseudostems [6]. Poor management of these residues can contribute to waste accumulation and may increase environmental and disease-related risks [14,46]. Banana peels account for a substantial proportion of the fruit mass and contain organic matter and nutrients that can be recovered through composting and vermicomposting [47].

Vermicomposting provides a means of converting banana peel waste into a stabilized organic amendment. The process can reduce waste accumulation while recovering nutrients for agricultural use, consistent with circular-bioeconomy principles [48]. Successful decomposition depends on factors such as moisture, pH, C:N ratio, temperature, aeration, and oxygen availability at optimal ranges [37].

Banana peels contain substantial amounts of carbohydrates and fiber and can provide K and other nutrients to the composting process (Table 2). Their chemical composition varies with banana variety, maturity, growing conditions, and processing method [49,50]. Therefore, the nutrient value of banana peel-derived amendments should be determined from the final processed material rather than assumed from the composition of fresh peels alone.

The use of banana residues as soil amendments is not new. Farmers in several parts of Asia and Africa have traditionally incorporated banana residues and other organic wastes into soils or compost systems [51]. Vermicomposting provides an opportunity to formalize this nutrient-recovery practice by converting banana residues into a more stabilized material with a potentially more predictable nutrient-release pattern.

Table 2: Nutritive value of banana peels, highlighting the composition of carbohydrates, proteins, starch, fiber, lipids, and ash. (Adapted from Saeed & Saeed, 2025) [49].

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

Preparation of Banana Peel Vermicompost

Banana peel vermicomposting involves preparing the peels, adjusting the substrate conditions, introducing suitable earthworms, and allowing sufficient time for decomposition and stabilization. Chopping the fresh peels can increase their surface area and facilitate decomposition. Pre-composting with cow dung for several days may help reduce excessive heat and volatile compounds before earthworms are introduced [52,53].

Eisenia fetida and *Eudrilus eugeniae* have been used for vermicomposting banana residues [52]. Reported operating conditions include moisture contents of approximately 60–80%, temperatures of 20–30°C, and a near-neutral pH of 6.5–7.5 [33]. *The material may be turned periodically during a production period of approximately 45–60 days* [54]. The resulting banana peel vermicompost has been reported to contain approximately 1.2–1.8% N, 0.6–0.9% P, and 1.8–2.3% K, although nutrient concentrations depend on the feedstock and processing conditions [51,53]. These characteristics indicate that banana peel vermicompost may serve as a source of nutrients and organic matter. However, its agronomic value should be evaluated using standardized chemical characterization and field-based crop-response studies.

3.3 Benefits of Vermicompost

Vermicompost has been associated with improvements in soil biological activity, plant growth, and crop yield across a range of crops and production systems. For example, vermicompost-amended plots in Cameroon supported larger earthworm populations than plots treated with poultry manure, NPK fertilizer, or no amendment, suggesting potential benefits for soil biological activity [55]. A meta-analysis of 68 studies reported that vermicompost application at rates of 0–20% improved vegetable seed germination and several seedling growth traits [56,57]. The same analysis reported yield increases of 38.92% in radish, 38.26% in pepper, 28.11% in cabbage, 18.36% in tomato, and 15.30% in cucumber. In cereals, reported net-benefit increases were 86% for maize and 152% for wheat under the conditions examined. Responses to vermicompost also vary according to soil conditions. In calcareous soil, vermicompost application increased onion plant height, bulb diameter, leaf area, and bulb weight compared with untreated soil [57]. A long-term field study in Bangladesh reported reductions in soil salinity together with improvements in soil N, P, and K across several crop-production systems [58]. In arsenic-contaminated soil, combining vermicompost with *Bacillus songklensis* and *B. siamensis* increased peanut pod yield by 11% and reduced arsenic accumulation in stems and seeds by 25–30% [59].

Overall, the available evidence indicates that vermicompost can improve soil properties and crop performance, but the magnitude of the response varies with crop species, application rate, soil characteristics, feedstock, and environmental conditions. Therefore, reported yield increases should not be interpreted as a universal response to vermicompost application.

Effects of Banana Peel Vermicompost

Banana peel-derived vermicompost outperforms inorganic fertilizers in microbial abundance and activity, nutrient retention, and plant growth, while minimizing chemical residues [60]. In maize, it increased plant height by 26.3% and root biomass by 37.8% relative to synthetic fertilizers, alongside 19.5% higher organic matter and 24.8% higher microbial population in amended soils [48].

Studies have also reported elevated nitrogen and potassium levels in banana peel-amended compost [51]. In okra (*Abelmoschus esculentus*), it raised chlorophyll content by 28% and fruit yield by 32% relative to chemical fertilizer controls, while reducing heavy-metal uptake via the chelating properties of its humic substances [61]. In germination trials with fenugreek, green gram, and chickpea, vermicompost consistently

outperformed conventional compost (95% vs. 80% germination for fenugreek; 90% vs. 80% for green gram and chickpea [62]), with electron microscopy confirming higher oxygen and silica content associated with improved soil structure and plant resistance [62]. These effects also support the circular bioeconomy by turning waste into a resource while sustaining soil health and nutrient cycling [52–54].

3.4 Vermicompost Compared with Other Organic and Synthetic Fertilizers

Synthetic fertilizers, including nitrogenous, phosphatic, potassic, and blended formulations, remain central to global food production [4,16]. However, concerns about nutrient losses, soil degradation, environmental impacts, and increasing input costs have increased interest in organic amendments such as vermicompost, FYM, and biofertilizers [15,16]. Comparative studies indicate that vermicompost can produce plant-growth and yield responses similar to, or in some cases greater than, those obtained with synthetic fertilizers [30,63]. In a tomato experiment involving six treatments, vermicompost alone produced greater responses than chemical fertilizer alone, while the combination of vermicompost and chemical fertilizer produced the strongest overall response [64]. These findings suggest that organic and synthetic inputs may provide complementary functions rather than necessarily acting as direct substitutes.

Vermicompost has also been reported to contain higher concentrations of some nutrients and humic substances than FYM [65]. As shown in Table 3, vermicompost contained higher concentrations of N, P₂O₅, K₂O, Fe, Mn, Zn, and Cu than FYM, while Ca and Mg concentrations were similar or lower. Vermicompost also had a lower C:N ratio than FYM, indicating a greater degree of organic-matter stabilization [65]. However, nutrient concentration alone does not determine fertilizer effectiveness. Crop response depends on nutrient availability, application rate, soil properties, timing, and environmental conditions. Synthetic fertilizers may provide nutrients rapidly, whereas organic amendments can contribute organic matter and support soil biological processes. Thus, combining the two approaches may be useful where the objective is to provide readily available nutrients while maintaining or improving soil organic matter.

Banana peel-derived amendments are particularly relevant because banana peels contain relatively high concentrations of K [66]. Their use in vermicomposting may therefore provide an opportunity to recover nutrients from agricultural waste and return them to crop-production systems. The possible integration of banana peel vermicompost with nanotechnology is considered in the following section.

Table 3: Comparative analysis of nutritive value between vermicompost and farmyard manure [65].

Parameters	Vermicompost	Farmyard Manure
N (%)	1.6	0.5
P ₂ O ₅ (%)	0.7	0.2
K ₂ O (%)	0.8	0.5
Ca (%)	0.5	0.9
Mg (%)	0.2	0.2
Fe (ppm)	175.0	146.5
Mn (ppm)	96.5	69.0
Zn (ppm)	24.5	14.5
Cu (ppm)	5	2.8
C:N ratio	15.5	31.3

4 Nanofertilizers: Principles and Preparation

Nanotechnology involves the manipulation of materials at approximately 1–100 nm, where materials can exhibit physical and chemical properties that differ from those of their bulk counterparts [67]. In agriculture, nanotechnology has been investigated for nutrient delivery, crop protection, sensing, and other

applications [7]. Among these applications, nanofertilizers have received attention because their physical and chemical properties may allow nutrient release and delivery to be modified.

Nanofertilizers can be produced by incorporating nutrients into nanoscale carriers or by converting nutrients themselves into nanoscale materials [8,68]. Potential carrier materials include zeolites, clay minerals, and chitosan, while examples of nutrient-based nanoparticles include iron oxide (FeO), zinc oxide (ZnO), and hydroxyapatite nanoparticles [69,70]. Two approaches are particularly relevant to nanofertilizer design: controlled nutrient encapsulation and nanosizing. Encapsulation involves incorporating nutrients within or onto a carrier to regulate their release, whereas nanosizing reduces particle dimensions and increases the surface-area-to-volume ratio [8]. These characteristics can influence nutrient dissolution, mobility, and availability to plants.

For example, urea–hydroxyapatite nanohybrids have been reported to extend N-release duration and reduce ammonia losses [71]. Similarly, zeolite-based nanofertilizers have been reported to release nutrients gradually and reduce nitrate leaching in sandy soils [8]. However, the performance of nanofertilizers depends on particle size, chemical composition, crystallinity, surface properties, nutrient concentration, application method, and soil conditions [72].

4.1 Chemical Composition and Type of Nanofertilizers

Nanofertilizers can be broadly classified according to whether nutrients are incorporated into nanocarriers or directly formulated as nanoscale nutrient materials [7,68,72]. Commonly investigated materials include iron (III) oxide (Fe₂O₃) nanoparticles, ZnO nanoparticles, hydroxyapatite nanoparticles, zeolites, clay minerals, and chitosan-based carriers. The choice of material influences nutrient-release characteristics and plant availability. Smaller particles generally have a larger specific surface area, which can influence dissolution and interaction with plant and soil surfaces. In contrast, particle structure and crystallinity can affect the rate at which nutrients are released [72]. These properties provide a basis for designing nanofertilizers that release nutrients at a rate that more closely corresponds to crop demand. However, increased nutrient availability does not necessarily imply greater agronomic benefit. Application concentration, particle characteristics, soil properties, and crop species all influence plant responses and potential environmental effects.

4.2 Benefits and Limitations of Nanofertilizers

Several studies and meta-analyses have reported positive effects of nanofertilizers on crop growth, yield, and nutrient-use efficiency. Reported yield responses vary among crops and formulations, with some meta-analyses estimating yield increases of approximately 18–55% [8,73]. For example, Fe₂O₃ nanoparticles have been reported to increase root length, chlorophyll concentration, and Fe uptake in peanut, while ZnO nanoparticles have increased tomato yield and improved selected nutritional traits [74]. Nano-Fe has also been associated with increases in wheat grain yield and grain Fe concentration [70,75].

Nanofertilizers may also reduce nutrient losses. Some studies have reported reductions in nitrate leaching and ammonia losses following the use of nano-enabled nutrient formulations [76]. However, these benefits are not universal. High concentrations of some nanoparticles, including ZnO and CuO, may negatively affect soil microorganisms, indicating the importance of dose optimization and environmental assessment [9]. Evidence from African agricultural systems suggests that nano-enabled nutrient management may improve nutrient-use efficiency and crop yield while reducing fertilizer requirements [77]. However, most of the available evidence remains based on controlled experiments. Consequently, the performance of specific nanofertilizer formulations under different field conditions requires further evaluation.

4.3 Integration with Other Agricultural Technologies

Nanotechnology can also be combined with biological and organic inputs. Organic amendments such as vermicompost can improve soil structure, organic matter, and microbial activity, whereas nano-enabled nutrient systems may modify nutrient release and availability. The combination therefore has the potential to address different components of soil fertility management.

Evidence from integrated soil and crop management systems in China indicates that combining improved nutrient management with other agronomic practices can increase crop yields while reducing N use and greenhouse gas emissions [78]. Similarly, studies combining vermicompost with water-retaining nano-enabled materials have reported improved drought resilience and crop yield [79]. These findings provide a basis for considering the integration of vermicompost and nanotechnology. However, results from other crops, countries, or nano-enabled materials cannot automatically be extrapolated to banana peel-vermicompost nanofertilizers in Kenya. The performance and safety of the proposed formulation therefore needs to be evaluated under the specific soil, climate, crop, and management conditions in which it would be used.

5 Integration of Vermicompost and Nanofertilizers

The integration of banana peels-vermicompost with nanotechnology provides a potential approach for combining organic nutrient recovery with controlled nutrient delivery. Banana peels provide an accessible source of organic matter and nutrients, while vermicomposting can stabilize the material and improve its suitability as a soil amendment. Nanotechnology may further modify nutrient release and availability. The potential value of combining these approaches therefore lies in their complementary functions rather than in nanotechnology alone.

Potential Benefits and Approaches to Integration

Various approaches can be considered for integrating banana peel vermicompost with nanotechnology. These include physical nanosizing, chemical synthesis of nutrient-containing nanomaterials, and the use of banana-derived materials as carriers or reducing and stabilizing agents for nanoparticle production.

Physical nanosizing involves reducing the particle size of the processed material to increase its surface area [80]. In principle, greater surface area may influence nutrient dissolution and interaction with soil and plant surfaces. However, reducing an organic material to the nanoscale does not necessarily preserve all of the biological and chemical properties of the original vermicompost. The effects therefore depend on the processing method and the characteristics of the resulting material.

A second approach involves the extraction of nutrients or bioactive compounds from banana peel vermicompost followed by their incorporation into nanoscale formulations. Chelation or encapsulation may be used to modify nutrient mobility and release. Such formulations could potentially reduce nutrient losses and improve nutrient availability, although their effectiveness depends on the chemical structure and stability of the resulting formulation.

A third approach involves using banana peel-derived compounds in the synthesis or stabilization of nanoparticles. Banana peel extracts contain organic compounds that may function as reducing or stabilizing agents during the synthesis of certain nanoparticles. This approach may reduce the need for certain conventional chemical reagents and could provide an additional route for recovering value from banana-processing residues.

The proposed formulation pathway is illustrated in Fig. 2. In general, the process involves preparation of banana peel residues, vermicomposting, processing of the resulting material, and incorporation of the

processed material into a nano-enabled nutrient formulation. Fig. 3 summarizes the proposed interactions among vermicompost, nanomaterials, soil processes, and plant responses. The potential mechanisms of action include improved nutrient availability, modified nutrient-release rates, increased soil organic matter, improved soil biological activity, and greater water retention [29,31,40]. However, these mechanisms should be considered as proposed pathways rather than established outcomes for banana peel–vermicompost nanofertilizers unless they have been directly demonstrated experimentally.

Some studies have reported positive responses to nano-enabled formulations derived from organic materials, including increases in crop growth, nutrient uptake, and yield [81]. However, the available evidence does not yet establish that nanosizing consistently produces greater agronomic benefits than conventional vermicompost. Reported responses vary with formulation, particle characteristics, application rate, crop, soil type, and environmental conditions.

Therefore, the integration of vermicompost and nanotechnology should be viewed as an emerging research approach rather than as a proven technology for smallholder agriculture. Direct comparisons among conventional vermicompost, banana peel vermicompost, conventional fertilizers, and banana peel–vermicompost nanofertilizers are needed to determine whether nano-enabled formulations provide sufficient agronomic benefits to justify their additional processing requirements and costs.

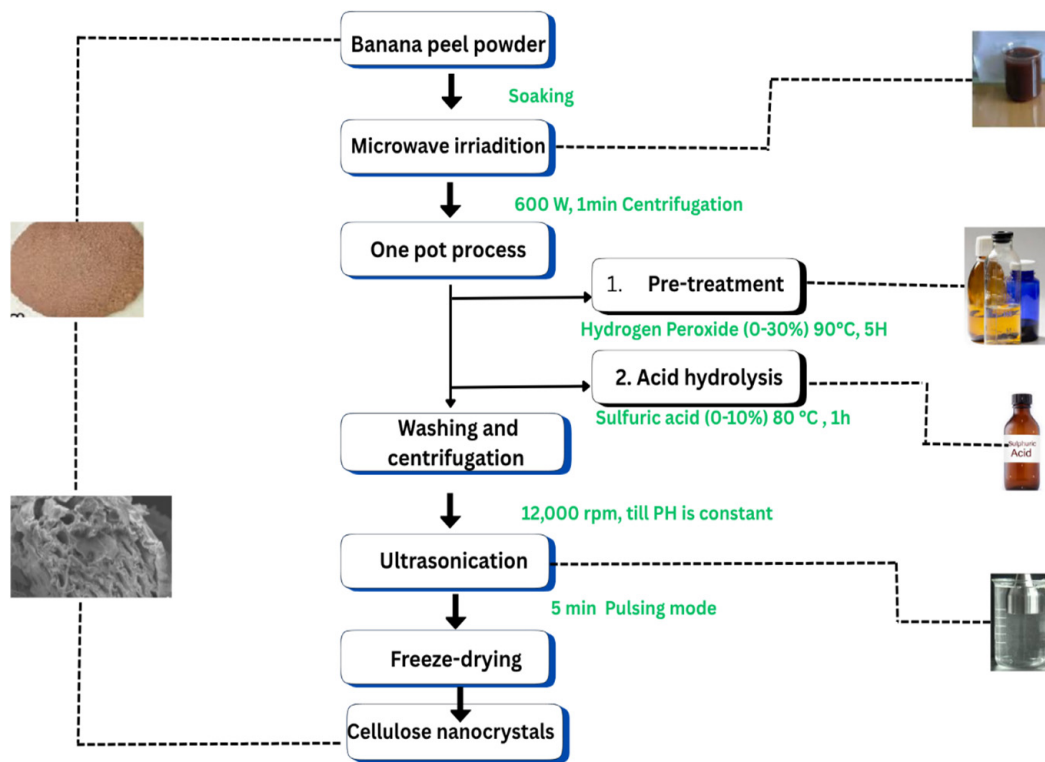


Figure 2: Proposed process for producing banana peel–vermicompost-based nanofertilizers. The process includes banana peel preparation, vermicomposting, processing of the vermicompost, and incorporation into a nano-enabled nutrient formulation.

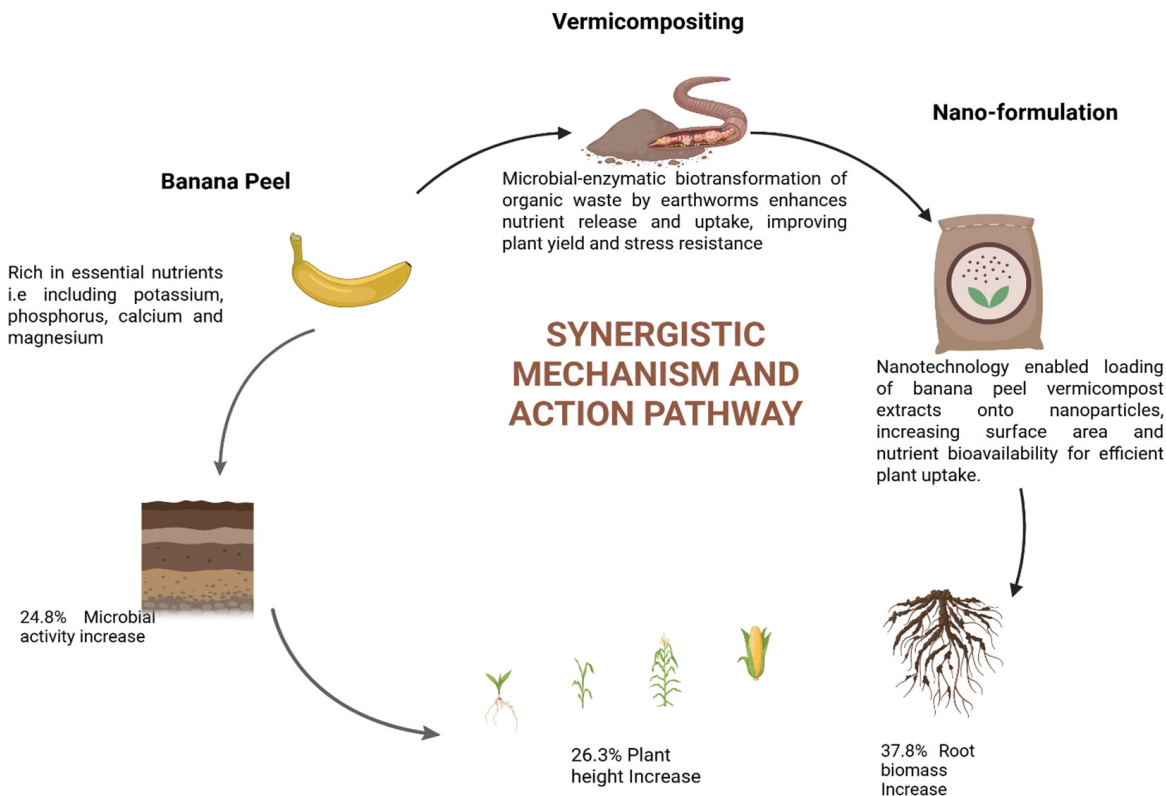


Figure 3: Proposed mechanisms through which banana peel-vermicompost nanofertilizers may influence soil and maize. Vermicomposting may contribute organic matter, nutrients, and microbial activity, whereas nano-enabled processing may modify nutrient availability and release. These changes may influence soil properties, nutrient uptake, plant growth, and yield. The pathways shown represent proposed mechanisms that require experimental validation.

6 Key Results and Application in Kenya

Maize (*Zea mays*) is an important food-security crop in Kenya and is widely grown in the Rift valley, Western, and Nyanza regions [82,83]. Most maize production is rainfed and undertaken by smallholder farmers, making production sensitive to rainfall variability and other climate-related stresses [44,82].

Several factors contribute to the yield gap, including limited access to improved seed, suboptimal agronomic practices, soil-fertility constraints, fertilizer costs, and climatic variability [84,85]. Declining soil organic matter can also reduce soil structure and water-holding capacity, increasing crop vulnerability to periods of water stress.

Kenya's agroecological diversity means that soil and climate conditions differ substantially among production regions. Maize varieties are therefore selected according to altitude, rainfall, temperature, and other local production conditions (Table 4). High-altitude areas such as Uasin Gishu and Nandi support maize varieties adapted to cooler conditions, whereas dryland counties such as Makueni, Baringo, and Kitui require varieties that are better suited to lower and more variable rainfall conditions [83]. These differences are important when considering the use of organic and nano-enabled fertilizers. A formulation that performs well under controlled conditions or in one soil type may not produce the same response elsewhere. Field evaluation should therefore consider soil properties, rainfall patterns, maize variety, fertilizer rate, application method, and other management practices.

Banana production provides an additional opportunity for nutrient recovery. Banana peels and other banana residues are locally available in several Kenyan production areas and could potentially be processed into organic amendments through vermicomposting [43,48]. Vermicompost has also been reported to improve maize growth, chlorophyll content, and grain yield under Kenyan conditions [86]. These characteristics provide a basis for investigating banana peel–vermicompost as a locally derived soil amendment. The addition of nanotechnology may potentially modify nutrient release or availability. However, evidence specifically evaluating banana peel–vermicompost nanofertilizers in Kenyan maize production remains limited. Therefore, the application of this technology should currently be considered a research opportunity rather than a validated recommendation for smallholder farmers.

Table 4: Maize varieties suited to Kenya’s varied agro-ecological zones, classified according to altitude and representative counties [83].

Maize Zone	Altitude	Representative Counties	Maize Varieties
Highlands	1500–2100 m	Uasin Gishu, Nandi, Trans-Nzoia,	H6218, H6213, Pannar 691
Medium/Transitional	1000–1800 m	Bungoma, Busia Kakamega	KH500-33A, H520, H516
Dryland	800–1200 m	Makueni, Baringo, Kitui	Composite, DH01, Katumani
Lowlands	0–1200 m	Kilifi, Mombasa, Lamu	PH1, PH4

Potential Applications and Research Opportunities

Banana peel–vermicompost nanofertilizers may provide an opportunity to recover nutrients from agricultural waste and return them to crop-production systems. This approach is consistent with circular-bioeconomy principles because it links waste management with nutrient recovery and soil fertility management. For Kenyan smallholder systems, locally available banana residues could potentially reduce dependence on externally sourced organic materials. However, local production does not necessarily mean that a nano-enabled formulation will be inexpensive. Processing, characterization, equipment, quality control, and application requirements may increase production costs.

The approach may also have applications beyond maize. Evidence from other organic and nano-enabled nutrient-management systems suggests that integrated formulations can influence crop growth, nutrient uptake, and stress tolerance [56–59]. However, evidence from other crops and countries should be considered preliminary when assessing their relevance to Kenyan smallholder systems. Future studies should therefore compare banana peel–vermicompost nanofertilizers with conventional vermicompost and recommended synthetic fertilizer practices under field conditions. Such studies should evaluate crop yield, nutrient-use efficiency, soil properties, economic returns, environmental effects, and potential risks over multiple growing seasons.

7 Limitations, Risks, and Research Needs

Despite the potential benefits discussed above, several limitations need to be addressed before banana peel–vermicompost nanofertilizers can be considered for wider agricultural use.

7.1 Environmental and Safety Considerations

The long-term environmental safety of nanomaterial-based fertilizers remains incompletely understood. A one-year incubation study in loamy soil found that silver nanoparticles altered the relative

abundance of several major bacterial groups, including *Actinobacteria*, *Bacteroidetes*, and *beta-Proteobacteria*, with responses varying over time [87]. Such findings indicate that nanoparticle effects on soil microbial communities may depend on exposure duration and environmental conditions. The effects of metal-oxide and biosynthesized nanoparticles on soil microorganisms and non-target organisms over repeated growing seasons remain particularly uncertain [88]. This is important for banana peel–vermicompost nanofertilizers because the environmental behavior of the final formulation will depend on the type, concentration, size, surface properties, and stability of the nanomaterials used. Short-term studies may demonstrate agronomic responses, but they cannot establish long-term ecological safety. Future studies should therefore monitor soil microbial communities, nanoparticle persistence, nutrient accumulation, plant uptake, and potential effects on non-target organisms over multiple growing seasons.

7.2 Economic and Adoption Constraints

Economic feasibility is another important consideration. The production of nanofertilizers may require specialized processing, equipment, quality control, and characterization beyond those required for conventional vermicomposting. Some estimates indicate that nanofertilizers and nano-pesticides may cost two to three times more than conventional products [67]. However, the economic performance varies among formulations and depends on whether improvements in nutrient-use efficiency or crop yield are sufficient to offset the additional production costs [89]. These costs may be particularly important for resource-limited smallholder farmers. Although banana peels and other organic feedstocks may be locally available, nanoscale processing may require equipment and technical expertise that are not readily accessible at farm level. Production systems would therefore need to consider whether processing is undertaken on-farm, through farmer cooperatives, or by specialized facilities. Limited farmer awareness may also constrain adoption. Farmers would require information on product quality, application rates, handling procedures, expected benefits, and potential risks. Extension services and appropriate regulatory frameworks would therefore be important components of any future scale-up strategy [67,76].

7.3 Evidence and Field-Validation Gaps

A major limitation of the current evidence base is that many studies have been conducted under controlled greenhouse or pot conditions rather than in multi-season field trials under smallholder conditions [90]. Field environments introduce variation in rainfall, temperature, soil properties, crop management, and nutrient losses that may alter the performance of nano-enabled fertilizers. Comparisons among studies are also complicated by differences in nanoparticle characterization, particle size, formulation, dosage, application method, and experimental conditions. Standardized protocols for nanomaterial characterization and field testing would improve the comparability and reproducibility of results [90].

Future research should prioritize multi-season field trials across representative Kenyan agroecological zones. These trials should compare banana peel–vermicompost nanofertilizers with conventional vermicompost, recommended synthetic fertilizer practices, and appropriate integrated treatments. Measurements should include crop yield, nutrient-use efficiency, soil fertility, soil microbial activity, economic returns, and environmental safety. Research should also examine the development of low-cost and biodegradable nanomaterials, optimize application rates, and identify formulations that balance agronomic performance with environmental safety [8]. Such work would help determine whether the proposed technology can provide benefits that are sufficiently large and consistent to justify its additional processing requirements. Ultimately, wider adoption will depend not only on technical performance but also on economic feasibility,

farmer acceptance, regulatory frameworks, extension capacity, and access to appropriate production and quality-control infrastructure.

8 Conclusion

Soil degradation, low nutrient-use efficiency, and limited access to agricultural inputs continue to constrain maize production in Kenyan smallholder farming systems. This review examined the potential of banana peel–vermicompost-based nanofertilizers as an approach that combines nutrient recovery from organic waste with the potential for more controlled nutrient delivery. The evidence reviewed indicates that vermicompost can improve soil organic matter, nutrient availability, biological activity, and crop growth. Banana peel is a potentially useful feedstock because it contains organic matter and nutrients, particularly K, and can be converted into a stabilized amendment through vermicomposting. Nanofertilizer technologies may further modify nutrient release and availability. However, evidence for the combined banana peel–vermicompost nanofertilizer approach remains limited, particularly under Kenyan field conditions. Reported improvements in plant growth, soil properties, and crop yield provide a basis for further investigation, but these results should not be interpreted as evidence that the technology is already suitable for widespread smallholder adoption. A substantial amount of available evidence comes from controlled experiments, and important questions remain regarding long-term environmental safety, formulation stability, production costs, application rates, and performance across different soils and agroecological zones. Future research should therefore focus on multi-season field trials in representative Kenyan maize-producing regions. These studies should compare nano-enabled formulations with conventional vermicompost and recommended fertilizer practices while assessing crop productivity, nutrient-use efficiency, soil health, economic returns, and environmental safety. Overall, banana peel–vermicompost nanofertilizers represent a promising research direction for linking agricultural-waste recovery with soil fertility management. Their contribution to sustainable maize production in Kenya will depend on whether future field and economic evaluations demonstrate consistent agronomic benefits that can be achieved safely and at an acceptable cost.

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Abbreviations

°C	Degree Celsius
%	Percentage
ABA	Abscissic Acid
C:N	Carbon to Nitrogen Ratio
CNCs	Cellulose Nanocrystals
Cm	Centimeters
Cu	Copper
Fe	Iron
Fe ₂ O ₃	Iron(III) Oxide
KASEP	Kenya Agricultural Sector Extension Policy
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Nm	Nano Material
NUE	Nutrient Use Efficiency
P	Phosphorus
K	Potassium
Zn	Zinc
ZnO	Zinc Oxide

References

1. Orawo F, Okello D, Olwande J, Tesfaye K. Determinants of soil testing decisions among smallholder maize farmers in western Kenya. *Front Sustain Food Syst.* 2026;10:1813147. [[CrossRef](#)].
2. Rhodes CJ. Soil erosion, climate change and global food security: challenges and strategies. *Sci Prog.* 2014;97(2):97–153. [[CrossRef](#)].
3. Kaumbutho PG, Gebresenbet G, Simalenga TE. Overview of conservation tillage practices in East and Southern Africa. In: *Conservation tillage with animal traction: A resource book of animal traction network for Eastern and Southern Africa*. Harare, Zimbabwe: ATNESA; 1999.
4. Delgado A, Quemada M, Mateos L, Villalobos FJ. Fertilization with phosphorus, potassium, and other nutrients. In: *Principles of agronomy for sustainable agriculture*. Cham, Switzerland: Springer; 2024. p. 415–37. [[CrossRef](#)].
5. Larney FJ, Angers DA. The role of organic amendments in soil reclamation: a review. *Can J Soil Sci.* 2012;92(1):19–38. [[CrossRef](#)].
6. Zaini NSM, Yaacob JS, Gengatharan A, Dahlal NM, Azman EM, Mohsin AZ, et al. Banana waste and its circularity potential: a sustainable source of alternative foods, bioactive compounds, and food technological applications. *Sci Agric.* 2025;82:e20250029. [[CrossRef](#)].
7. Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, Rehman HU, et al. Nanotechnology in agriculture: current status, challenges and future opportunities. *Sci Total Environ.* 2020;721:137778. [[CrossRef](#)].
8. Al-Juthery HWA, Lahmod NR, Al-Taei RAHG. Intelligent, nano-fertilizers: a new technology for improvement nutrient use efficiency (article review). *IOP Conf Ser Earth Environ Sci.* 2021;735(1):012086. [[CrossRef](#)].
9. Rashid M, Naveed M, Hussain M. Impact of metal oxide nanoparticles on soil microbial activity and organic matter decomposition. *Environ Sci Pollut Res.* 2017;95:23456.
10. Buringh P. Introduction to the study of soils in tropical and subtropical regions. 2nd ed. Wageningen, The Netherlands: Centre for Agricultural Publishing and Documentation; 1970. [[CrossRef](#)].
11. Flores BM, Staal A, Jakovac CC, Hirota M, Holmgren M, Oliveira RS. Soil erosion as a resilience drain in disturbed tropical forests. *Plant Soil.* 2020;450(1):11–25. [[CrossRef](#)].
12. Lal R. Sustainable management of soil resources in the humid tropics. Tokyo, Japan: United Nations University Press; 1995.
13. Musa IO, Samuel JO, Adams M, Abdulsalam M, Nathaniel V, Maude AM, et al. Soil erosion, mineral depletion and regeneration. In: *Prospects for soil regeneration and its impact on environmental protection*. Cham, Switzerland: Springer; 2024. p. 159–72. [[CrossRef](#)].

14. Kopittke PM, McKenna BA, Sanchez PB, Gonzaga NR, Asio VB, Aguila DNS, et al. The hidden costs of soil degradation: threats to global food security and planetary health. *ACS Environ Au.* 2026;6(4):539–52. [[CrossRef](#)].
15. Amirahmadi E, Ghorbani M. Unpacking the trade-offs: a meta-analysis of soil fertility, crop yield, and greenhouse gas emissions across fertilizer types (organic, mineral) and cropping systems. *Plants.* 2025;14(19):3005. [[CrossRef](#)].
16. Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W. How a century of ammonia synthesis changed the world. *Nat Geosci.* 2008;1(10):636–9. [[CrossRef](#)].
17. Rana L, Kumar M, Rajput J, Kumar N, Sow S, Kumar S, et al. Nexus between nanotechnology and agricultural production systems: challenges and future prospects. *Discover Appl Sci.* 2024;6(11):555. [[CrossRef](#)].
18. Wan NF, Fu L, Dainese M, Kiær LP, Hu YQ, Xin F, et al. Pesticides have negative effects on non-target organisms. *Nat Commun.* 2025;16:1360. [[CrossRef](#)].
19. Rehman S, De Castro F, Aprile A, Benedetti M, Fanizzi FP. Vermicompost: Enhancing plant growth and combating abiotic and biotic stress. *Agronomy.* 2023;13(4):1134. [[CrossRef](#)].
20. Panday D, Bhusal N, Das S, Ghalehgalabbahani A. Rooted in nature: the rise, challenges, and potential of organic farming and fertilizers in agroecosystems. *Sustainability.* 2024;16(4):1530. [[CrossRef](#)].
21. Masso C, Nziguheba G, Mutegi J, Galy-Lacaux C, Wendt J, Butterbach-Bahl K, et al. Soil fertility management in sub-Saharan Africa. In: *Sustainable agriculture reviews*. Cham, Switzerland: Springer; 2017. p. 205–31. [[CrossRef](#)].
22. Kaliba ARM, Verkuijl H, Mwangi W. Factors affecting adoption of improved maize seeds and use of inorganic fertilizer for maize production in the intermediate and lowland zones of Tanzania. *J Agric Appl Econ.* 2000;32(1):35–47. [[CrossRef](#)].
23. Molotoks A, Smith P, Dawson TP. Impacts of land use, population, and climate change on global food security. *Food Energy Secur.* 2021;10:e261. [[CrossRef](#)].
24. Merchant EV, Odendo M, Maiyo N, Govindasamy R, Morin XK, Simon JE, et al. An evaluation of nutrition, culinary, and production interventions using African indigenous vegetables on nutrition security among smallholder farmers in Western Kenya. *Front Nutr.* 2023;10:1154423. [[CrossRef](#)].
25. Begna T, Wakweya RB. Mitigating climate change impacts on food security via climate-smart agriculture. *Plant Stress.* 2026;19:101152. [[CrossRef](#)].
26. Sharma B, Tiwari S, Kumawat KC, Cardinale M. Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: potentiality and their limitations. *Sci Total Environ.* 2023;860:160476. [[CrossRef](#)].
27. Domínguez J, Edwards CA. Vermicomposting organic wastes: a review. In: Shakir SH, Mikhail WZA, editors. *Soil zoology for sustainable development in the 21st century*. Safat, Kuwait: The Scientific Cultural Society of Kuwait; 2004. p. 369–95.
28. Fornes F, Mendoza-Hernández D, García-de-la-Fuente R, Abad M, Belda RM. Composting versus vermicomposting: a comparative study of organic matter evolution through straight and combined processes. *Bioresour Technol.* 2012;118:296–305. [[CrossRef](#)].
29. Enebe MC, Erasmus M. Vermicomposting technology—A perspective on vermicompost production technologies, limitations and prospects. *J Environ Manage.* 2023;345:118585. [[CrossRef](#)].
30. Suthar S. Influence of vermicompost on growth, yield and quality of garlic (*Allium sativum* L.) under field conditions. *J Appl Sci Res.* 2009;5(11):1695–702.
31. Pathma J, Sakthivel N. Microbial diversity of vermicompost bacteria that exhibit useful agricultural traits and waste management potential. *SpringerPlus.* 2012;1(1):26. [[CrossRef](#)].
32. Prisa D, Jamal A. Vermicompost in agricultural production: mechanisms, importance, and applications. *Multidiscip Rev.* 2025;8(11):2025325. [[CrossRef](#)].
33. Kauser H, Khwairakpam M. Organic waste management by two-stage composting process to decrease the time required for vermicomposting. *Environ Technol Innov.* 2022;25:102193. [[CrossRef](#)].
34. Liégui GS, Cognet S, Djumyom GVW, Atabong PA, Noutadié JPF, Chamedjeu RR, et al. An effective organic waste recycling through vermicomposting technology for sustainable agriculture in tropics. *Int J Recycl Org Waste Agric.* 2021;10(3):203–14.
35. Pettinelli D. Vermicomposting: Indoor composting with worms. Storrs, CT, USA: University of Connecticut Soil Nutrient Analysis Laboratory; 2023.
36. Edwards CA, Lofty JR. *Biology of earthworms*. London, UK: Chapman and Hall; 1972. [[CrossRef](#)].

37. Katiyar RB, Sundaramurthy S, Sharma AK, Arisutha S, Ali Khan M, Sillanpää M. Optimization of engineering and process parameters for vermicomposting. *Sustainability*. 2023;15(10):8090. [CrossRef].
38. Edwards CA, Arancon NQ, Sherman R. *Vermiculture technology: earthworms, organic wastes, and environmental management*. Boca Raton, FL, USA: CRC Press; 2011.
39. Walia SS, Kaur T. Harvesting of vermicompost. In: *Earthworms and vermicomposting*. Singapore: Springer; 2024. p. 109–16. [CrossRef].
40. Punjab State Council for Science and Technology. *Vermiculture: Nutrient profile of vermicompost and farm yard manure*. 2010 [cited 2025 Jan 1]. Available from: http://agri.and.nic.in/vermi_culture.htm.
41. Sani M, Ibraheem A, Sani S, Abdulkadir A, Hassan I, Musa Z, et al. Primary nutrients status of three vermicomposts produced in a Nigerian Sahel region. *Bulg J Soil Sci*. 2024;9(1):83–91.
42. Amaral EJ, Pereira LMS, Lorençon E, Poggere GC, Agustini MAB, Edwiges T. Valorization of biowastes through pre-composting followed by vermicomposting with the addition of effective microorganisms. *Int J Environ Res*. 2024;19(1):9. [CrossRef].
43. Safi Organics. *Banana farming in Kenya*. 2024 [cited 2025 Jan 1]. Available from: <https://safiorganics.co.ke/blog/banana-farming-in-kenya/>.
44. Food and Agriculture Organization of the United Nations. *The state of food and agriculture 2024: Value-driven transformation of agrifood systems*. Rome, Italy: Food and Agriculture Organization of the United Nations; 2024.
45. Farming in Kenya. *Banana farming in Kenya: Planting guide and how to make money*. 2024 [cited 2025 Jan 1]. Available from: <https://agrovet.farmerstrend.co.ke/farming-guides/banana-farming-in-kenya-planting-guide-and-how-to-make-money/>. [CrossRef].
46. Priyanka K, Umesh M, Preethi K. Banana peels as a cost-effective substrate for fungal chitosan synthesis: optimisation and characterisation. *Environ Technol*. 2026;47(8):1197–211. [CrossRef].
47. International Institute of Tropical Agriculture. *Peels as feed and organic resource*. Ibadan, Nigeria: International Institute of Tropical Agriculture; 2025.
48. Sahin S, Kurt H. Effects of vermicompost applications on growth and phosphorus uptake of maize plants (*Zea mays* L.). *Fresenius Environ Bull*. 2020;29(12):11216–22.
49. Saeed R, Saeed M. Nutrient evaluation of banana peel biomass for biofertilizer development. *Asian J Agric Environ Res*. 2025;12(1):88–97.
50. Happi Emaga T, Andrianaivo RH, Wathelet B, Tchango JT, Paquot M. Effects of the stage of maturation and varieties on the chemical composition of banana and plantain peels. *Food Chem*. 2007;103(2):590–600. [CrossRef].
51. Kalemelawa F, Nishihara E, Endo T, Ahmad Z, Yeasmin R, Tenywa MM, et al. An evaluation of aerobic and anaerobic composting of banana peels treated with different inoculums for soil nutrient replenishment. *Bioresour Technol*. 2012;126:375–82. [CrossRef].
52. Yattoo AM, Ahmad Bhat S, Ali MN, Ahmad Baba Z, Zaheen Z. Production of nutrient-enriched vermicompost from aquatic macrophytes supplemented with kitchen waste: assessment of nutrient changes, phytotoxicity, and earthworm biodynamics. *Agronomy*. 2022;12(6):1303. [CrossRef].
53. Singh K. Concentration of nutrients in vermicompost derived from cow dung mixed with banana peels and vegetable waste. *World J Pharm Res*. 2023;12(5):1532–41.
54. Huang K, Li F, Li J, Helard D, Hirooka K. Rapid vermicomposting of fresh fruit and vegetable wastes using earthworm *Eisenia foetida*. *J Jpn Soc Civ Eng Ser G (Environ Res)*. 2012;68(7):III_113–20. [CrossRef].
55. Olougou MNE, Kungang NA, Ndzeshala ST, Ngone MA, Ngosong C. Exploring the fertilizer value of vermicompost and poultry manure to enhance soil health and yield of sweet bitter-leaf *Vernonia hymenolepis*. *Discover Soil*. 2025;2(1):42. [CrossRef].
56. Li F, Ren Y, Zhang Y, Zhang J, Wang XX. Exploring the potential of vermicompost in horticulture: a meta-analysis of seedling growth and sustainable cultivation. *Sci Hortic*. 2026;357:114658. [CrossRef].
57. Badr EA, Sayed SE, Mohamed MH. Integrated effects of vermicompost and town refuse on growth and nutritional status of onion cultivated in calcareous soil. *Sci Rep*. 2026;16(1):8620. [CrossRef].
58. Hossain ML, Shapna KJ, Li J, Kabir MH, Siddika F, Khandker S, et al. Transforming agriculture with vermicompost: 7-year empirical evidence from drought-prone and salinization-affected regions of Bangladesh. *J Clean Prod*. 2025;508:145595. [CrossRef].

59. Van Chuong N. Effects of *Bacillus songklensis* and *Bacillus siamensis* WD-32 combined with vermicompost on soil fertility, growth, yield and arsenic accumulation in peanut. *Asian J Agric Biol*. 2025:e2025142. [\[CrossRef\]](#).
60. Annapoorani CA, Sindhu M. Tea dust powder into valuable organic fertilizer using *Eudrilus euginae*. *Asian J Dairy Food Res*. 2019;38(4):147–52. [\[CrossRef\]](#).
61. Tripathi G, Bhardwaj P. Decomposition of kitchen waste amended with cow manure using an epigeic species (*Eisenia fetida*) and an anecic species (*Lampito mauritii*). *Bioresour Technol*. 2004;92(2):215–8. [\[CrossRef\]](#).
62. Mohanapriya T, Sindhu M, Annapoorani CA. Comparative analysis of composting and vermicomposting from peel of *Musa acuminata*. *Int J Zool Investig*. 2021;7(2):792–800. [\[CrossRef\]](#).
63. Uma B, Malathi M. Vermicompost as a soil supplement to improve growth and yield of *Amaranthus* species. *Res J Agric Biol Sci*. 2009;5(6):1054–60.
64. Meenakumari K, Shehkar M. Effect of vermicompost and other fertilizers on growth, yield and nutritional status of tomato. *J Agric Sci*. 2012;8(2):45–52.
65. Theunissen J, Ndakidemi P, Laubscher C. Potential of vermicompost produced from plant waste on the growth and nutrient status in vegetable production. *Int J Phys Sci*. 2010;5(13):1964–73.
66. Nordin NA, Najwa NA, Fatimah N, Syazwani N. Development of organic fertilizer from banana peel, egg shell and yeast for the effective growth of chili plant. *Multidiscip Appl Res Innov*. 2022;3(2):302–11.
67. Mukhopadhyay SS. Nanotechnology in agriculture: prospects and constraints. *Nanotechnol Sci Appl*. 2014;7:63–71. [\[CrossRef\]](#).
68. Subramanian KS, Paulraj C, Natarajan S. Nanotechnological approaches in nutrient management. *Nanotechnol Appl Agric*. 2008;61:37–42.
69. DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. *Nat Nanotechnol*. 2010;5(2):91. [\[CrossRef\]](#).
70. Zulfiqar F, Navarro M, Ashraf M, Akram NA, Munné-Bosch S. Nanofertilizer use for sustainable agriculture: advantages and limitations. *Plant Sci*. 2019;289:110270. [\[CrossRef\]](#).
71. Kottegoda N, Sandaruwan C, Priyadarshana G, Siriwardhana A, Rathnayake UA, Berugoda Arachchige DM, et al. Urea-hydroxyapatite nanohybrids for slow release of nitrogen. *ACS Nano*. 2017;11(2):1214–21. [\[CrossRef\]](#).
72. Madlala NC, Khanyile N, Masenya A. Examining the correlation between the inorganic nano-fertilizer crystalline structure and nutrient release. *Front Plant Sci*. 2024;14:1263. [\[CrossRef\]](#).
73. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nat Nanotechnol*. 2018;13(8):677–84. [\[CrossRef\]](#).
74. Rui M, Ma C, Hao Y, Guo J, Rui Y, Tang X, et al. Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). *Front Plant Sci*. 2016;7:815. [\[CrossRef\]](#).
75. Huang X, Wang X, Liu X, Cheng L, Pan J, Yang X. Nanotechnology in agriculture: manganese ferrite nanoparticles as a micronutrient fertilizer for wheat. *Plants*. 2024;13(10):1395. [\[CrossRef\]](#).
76. Kah M, Hofmann T. Nano-enabled fertilizers: A review of current developments and future perspectives. *J Environ Qual*. 2019;48:1591–600.
77. Khundi Q, Jiang Y, Sun Y, Rui Y. Nanofertilizers for sustainable African agriculture: a global review of agronomic efficiency and environmental sustainability. *Nanomaterials*. 2025;15(5):390. [\[CrossRef\]](#).
78. Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, et al. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*. 2018;555(7696):363–6. [\[CrossRef\]](#).
79. Khalifa TH, Mariey SA, Ghareeb ZE, Khatab IA, Alyamani A. Effect of organic amendments and nano-zinc foliar application on alleviation of water stress in some soil properties and water productivity of barley yield. *Agronomy*. 2022;12(3):585. [\[CrossRef\]](#).
80. Toksha B, Sonawale VAM, Vanarase A, Bornare D, Tonde S, Hazra C, et al. Nanofertilizers: A review on synthesis and impact of their use on crop yield and environment. *Environ Technol Innov*. 2021;24:101986. [\[CrossRef\]](#).
81. Mostafa HS. Banana plant as a source of valuable antimicrobial compounds and its current applications in the food sector. *J Food Sci*. 2021;86(9):3778–97. [\[CrossRef\]](#).
82. Kipkulei HK, Bellingrath-Kimura SD, Lana M, Ghazaryan G, Baatz R, Matavel C, et al. Agronomic management response in maize (*Zea mays* L.) production across three agroecological zones of Kenya. *Agrosystems Geosci Environ*. 2024;7(1):e20478. [\[CrossRef\]](#).

83. Kenya Agricultural and Livestock Research Organization. Maize value chain: inventory of technologies, innovations and management practices (TIMPs). Nairobi, Kenya: Kenya Agricultural and Livestock Research Organization; 2022.
84. Njeru RW, Muli FW, Wanjiru J. Maize yield gaps in smallholder farming systems in Kenya: Analysis and policy implications. *Afr J Agric Res.* 2022;17(5):123–34.
85. Mutuku JM, Gichangi EM, Wanjohi R. Maize productivity and input use efficiency among smallholder farmers in Kenya. *Field Crops Res.* 2020;250:107776.
86. Mwangi L, Kamau R, Otieno S. Effects of vermicompost on maize growth, yield, and nutritional quality in smallholder farms. *Afr J Agric Res.* 2025;21(2):88–102.
87. Grün AL, Emmerling C. Long-term effects of environmentally relevant concentrations of silver nanoparticles on major soil bacterial phyla of a loamy soil. *Environ Sci Eur.* 2018;30(1):31. [[CrossRef](#)].
88. Rath S, Harshavardhan M, Srivastava P. A concise overview of effect of nanomaterials in soil and associated microbiota. *J Environ Nanotechnol.* 2024;13(2):183–93. [[CrossRef](#)].
89. Su Y, Zhou X, Meng H, Xia T, Liu H, Rolshausen P, et al. Cost-benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the efficiency of nanoformulations for widescale adoption. *Nat Food.* 2022;3(12):1020–30. [[CrossRef](#)].
90. Goyal A, Chavan SS, Mohite RA, Shaikh IA, Chendake Y, Mohite DD. Emerging trends and perspectives on nano-fertilizers for sustainable agriculture. *Discover Nano.* 2025;20:97. [[CrossRef](#)].