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REVIEW ARTICLE

Nutrient nourishment through organic approach: A critical review on foliar nutrition

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Abstract

Nutrients play a pivotal role in the growth, development and overall health of plants. However, the widespread use of inorganic fertilizers in modern agriculture has led to significant environmental and health concerns, including soil degradation, water contamination and the disruption of beneficial soil microbiota. These issues underscore the urgency of exploring alternative, sustainable fertilization methods. This review critically examines the potential of organic fertilizers in addressing the nutritional deficiencies in soil that are exacerbated by the reliance on inorganic inputs. Our research hypothesizes that organic fertilizers not only replenish essential nutrients but also restore soil health by enhancing microbial diversity and activity. This hypothesis is significant and timely, given the growing global demand for sustainable agricultural practices. For the first time, our synthesis reveals overlooked interdisciplinary connections between soil microbiology, plant nutrition and sustainable agricultural economics, offering a novel perspective on the integration of organic fertilizers into mainstream agricultural practices. The breakthrough identified in this review lies in the comprehensive understanding of how organic fertilizers contribute to long-term soil fertility and crop productivity, beyond merely supplying nutrients. Moreover, this review identifies promising business opportunities in the development and commercialization of organic fertilizers tailored to specific crop and soil needs. Prospective directions for further research include the exploration of advanced organic formulations and the assessment of their economic viability on a large scale.

Keywords

organic farming; foliar nutrition; sustainability; traditional formulation; liquid organic fertilizer

Introduction

Agricultural intensification, driven by the need to meet growing food, feed and fuel demands, has relied heavily on agrochemicals, irrigation and mechanization to maximize productivity. However, this approach has significantly increased resource consumption, degraded water and soil quality and caused widespread pollution (1). For instance, global fertilizer consumption rose from 79 million tons in 1961 to 190 million tons in 2019, contributing to resource overuse, including water, energy and minerals as well as pollution and soil degradation (2).

The world faces a daunting challenge: feeding a projected population of 9.7 billion by 2050. This challenge is exacerbated by the limited availability of key resources, with global phosphate reserves predicted to be depleted within the next 50 to 100 years. However, the intensive use of inorganic fertilizers has significantly increased resource consumption, with water use in agriculture rising by approximately 70 %, energy inputs by 30 % and the extraction of essential minerals, such as phosphates, by over 50 % globally. This approach has also contributed to the degradation of water and soil quality, with an estimated 60 % of global agricultural lands experiencing some level of soil degradation due to chemical inputs. Furthermore, the widespread application of these fertilizers has led to substantial pollution, with nitrate levels in groundwater exceeding safe drinking limits in many agricultural regions, resulting in harmful algal blooms and hypoxic zones in over 400 aquatic ecosystems worldwide (3). Moreover, the energy crisis has driven fertilizer prices up by 30 % over the past decade, leading to increased production costs for farmers and raising concerns about the long-term sustainability of these agricultural practices (4).

In response, there is a growing shift towards non-chemical nutrient sources such as biofertilizers, farmyard manure and composts, which are central to organic farming. However, organic farming systems typically yield 20 % to 40 % less than conventional systems, necessitating up to 1.5 times more land to achieve equivalent output (5). Additionally, the bulkiness and cost of organic inputs, such as groundnut cake and vermicompost, which can range from $100 to $300 per ton, make them less accessible to small-scale farmers (6). The foliar application of liquid organic manures facilitates the absorption of nutrients at a rate twenty times faster than soil application. The use of liquid organic manures proves effective in addressing temporary nutrient deficiencies (7). The use of these fertilizers can also reduce the need for synthetic inputs, which are associated with environmental problems such as nitrogen runoff, eutrophication and soil acidification. “According to the latest research study by BCC, the demand for Organic Fertilizers: Global Markets is estimated to increase from $9.7 billion in 2023 to reach $13.5 billion by 2028, at a compound annual growth rate (CAGR) of 6.8 % from 2023 through 2028.”

Aligning with the latest trends in sustainable agriculture, recent innovations such as insect rearing on biowaste for fish farming demonstrate the potential for integrating organic and sustainable practices. This method not only supports food production but also offers a competitive advantage by reducing feed costs by up to 50 % (8). The production of liquid organic manures involves various farm inputs and everyday household materials, resulting in significantly lower costs than chemical fertilizers and pesticides. Plants may be fed using foliar spray by directly administering liquid compositions to their leaves. Through their leaves, plants can take in necessary nutrients. Both the epidermis and the stomata allow for the absorption to occur. Additionally, foliar spraying encourages the soil's absorption of nutrients. Through foliar spraying of nutrients, it is also utilized to rectify nutritional imbalances (9).

Materials and Methods

The methodology for this study was taken from (10) and it involved the examination of several works on organic foliar nutrition from scientific databases (e.g., Pub-Med, Google Scholar, Scopus and Web of Science were used for data retrieval). A thorough study and assessment are also included to explain the effectiveness and functionality of several organic formulations.

There are 5 steps in the analysis process (Fig. 1). The initial phase was devoted to finding and gathering reliable information. The interpretation of the review's subject and setting within the narrative framework is the second phase. Understanding different viewpoints on organic foliar nutrition and its function in crop growth is part of the third phase. The comparative evaluation of diverse literature to create comprehensive research is the fourth phase. Lastly, to analyse the information and summarise organic foliar nourishment’s impact on crops and how organic foliar nourishment is profitable and sustainable.

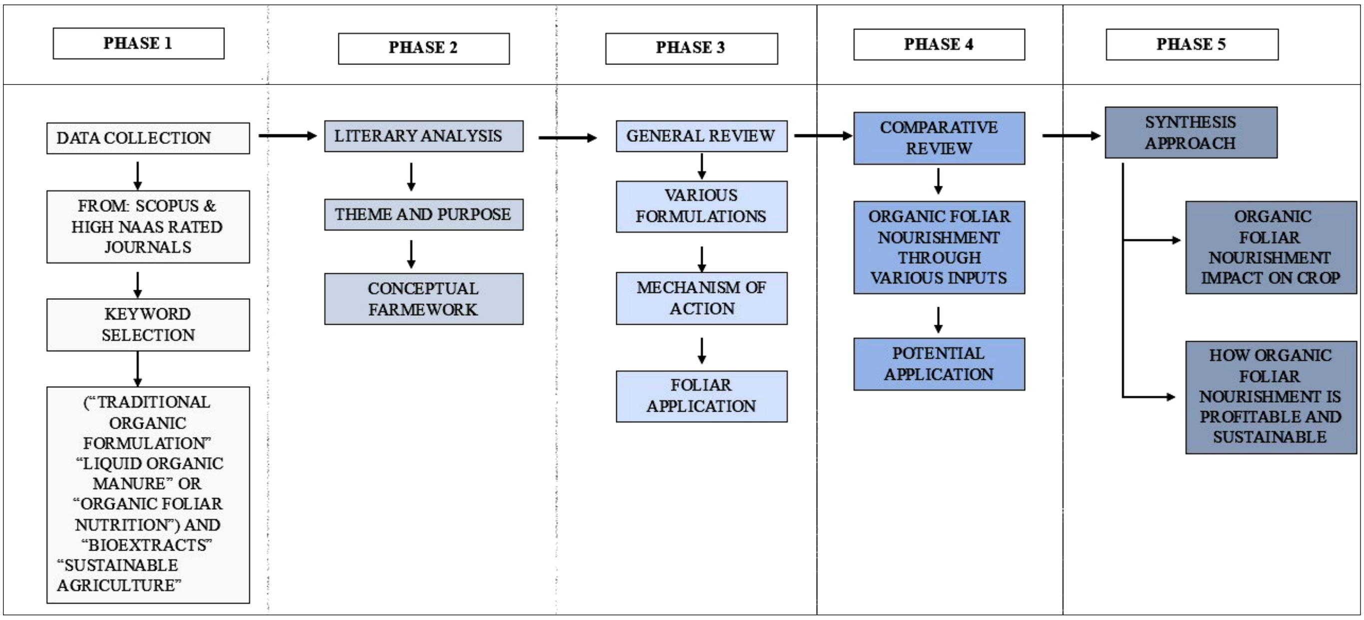

Fig. 1. Flowchart followed for literary review.

Results

Bibliometric analysis on research trends in organic foliar nutrition

Many searches with a wide range of keywords were carried out on different subjects. An extensive compilation of writings centred on traditional organic formulations, organic liquid fertilizers, their properties, mechanisms of action and applications. The collected literature was manually analyzed, cross-referenced and synthesized to provide a comprehensive report.

Bibliometric analysis was performed utilizing data sourced from Scopus and network visualization was executed through VOS viewer (Fig. 2 and 3). Citation analysis was specifically conducted on 5 units: documents, sources, authors, organizations and countries.

Out of the 3144 documents retrieved from Scopus, only those with more than 5 citations were utilized, resulting in 1557 documents. Within this set, 387 items exhibited a substantial interconnectivity.

When authors were utilized as the unit of analysis, 12431 authors were identified within the field of organic liquid fertilizers research. This number was refined based on citations and the number of documents published by each author.

Among the initially identified 6860 organizations, 51 organizations met the criteria of having a minimum of 3 documents and a minimum of 4 citations.

Panchagavya

The term '*panchagavya*' refers to an organic mixture made from 5 different ingredients: cow milk, clarified butter, curd,dung and urine. These ingredients are separately referred to as 'Gavya' and combined to produce the term '*panchagavya*' in Sanskrit. The Vedas are ancient sacred texts of Hinduism, composed in early Sanskrit and the Vrikshayurveda contain references to *panchagavya* (11). A unique concoction known as *panchagavya*, which is created from 5 cow by-products and a few additional components, could potentially be capable of helping plants develop and become more immune (12). *Panchagavya*, often referred to as Cowpathy, holds a significant place in ancient Indian rituals and the traditional Ayurvedic medical system. It has religious importance for Hindus and serves dual purposes in agriculture as both a fertilizer and an insecticide. Its use is strongly advocated in organic farming practices due to its promotion of environmentally sustainable agricultural methods(Fig.4) (13).

Panchagavya is a rich source of macronutrients such as nitrogen, phosphorus and potassium as well as micronutrients that are essential for plant growth and development. It also contains a variety of vitamins, amino acids

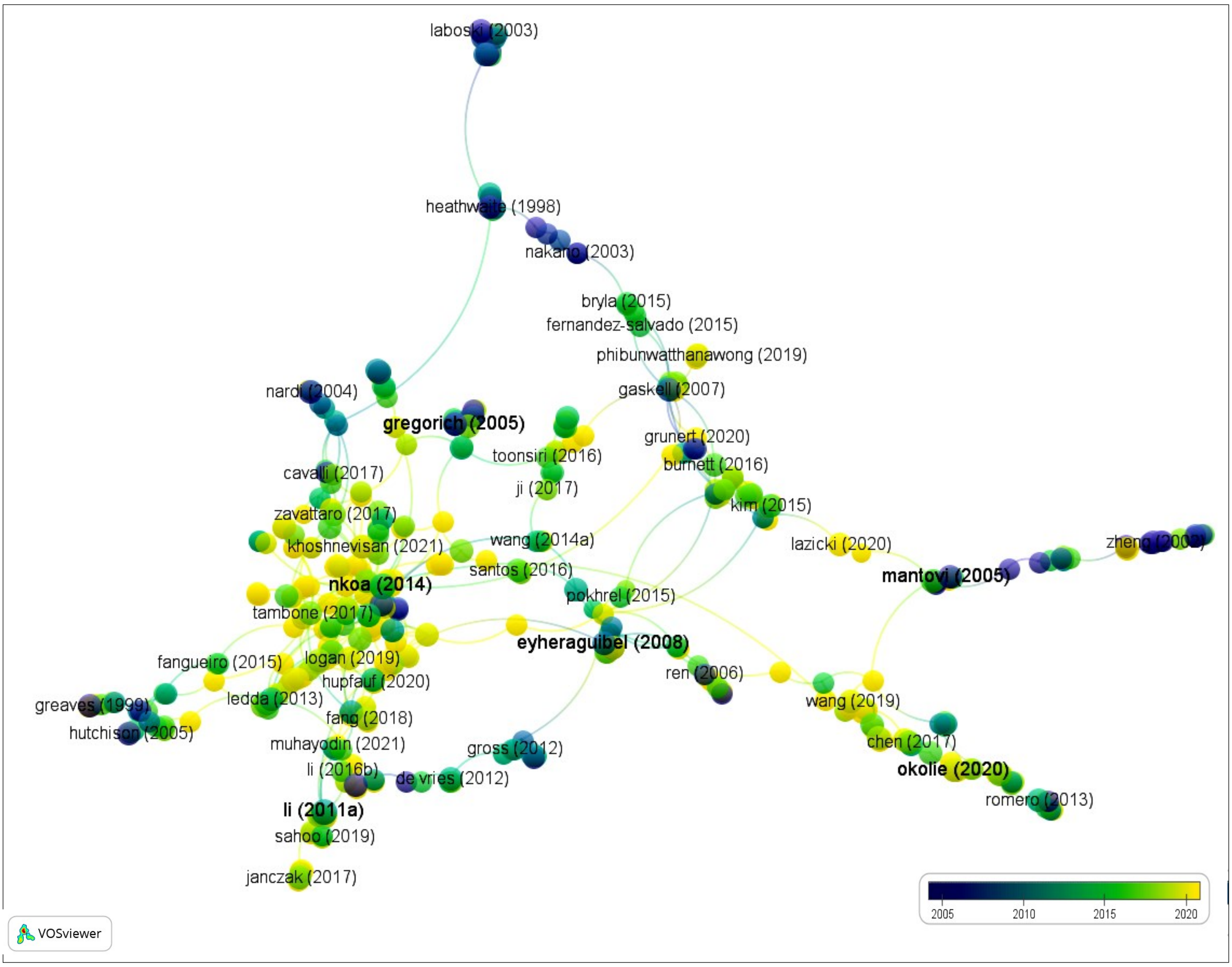

Fig. 2. Network visualization of documents as a unit of analysis related to liquid organic fertilizer.

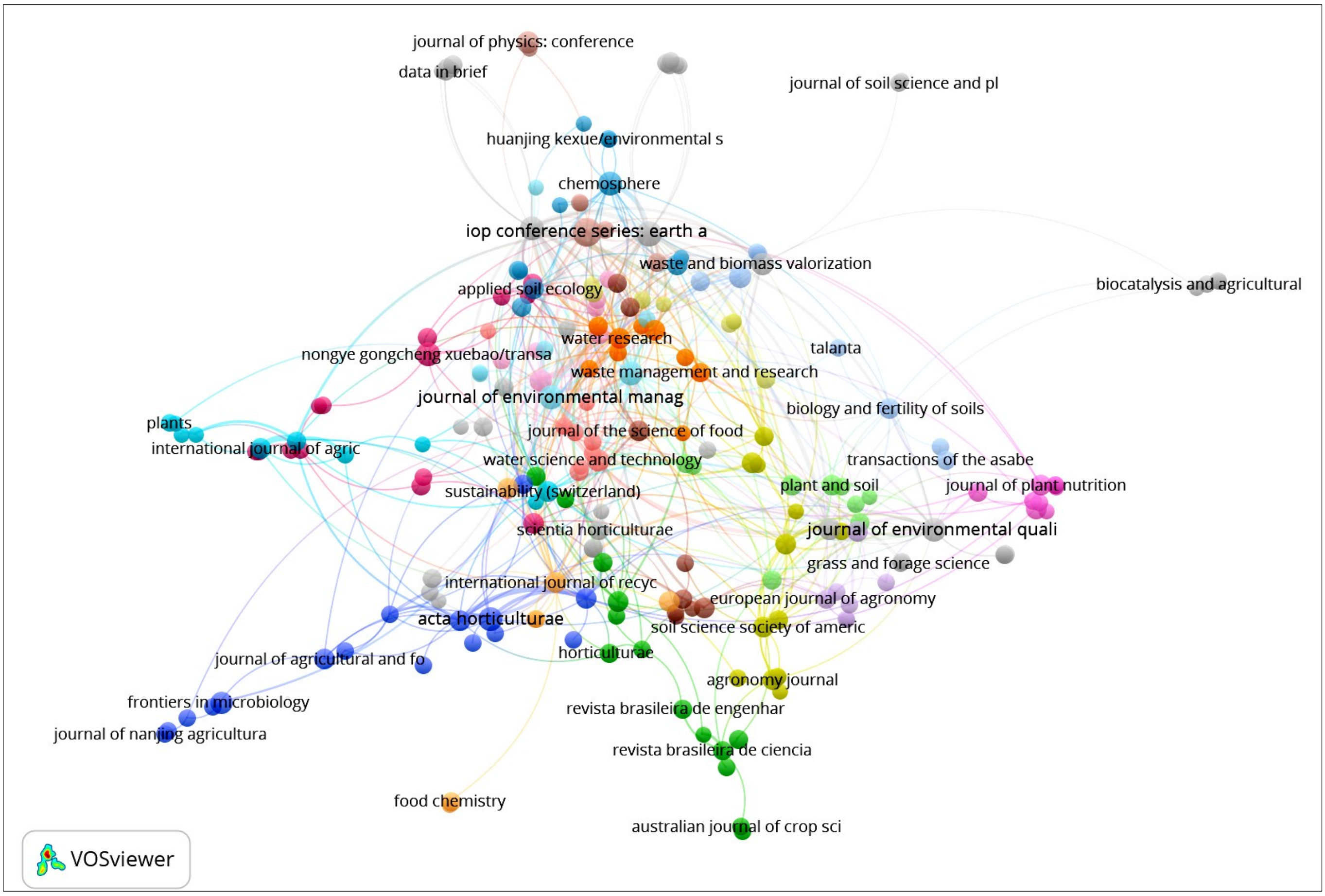

Fig. 3. Network visualization of sources like journals/institutions as a unit of analysis related to liquid organic fertilizer.

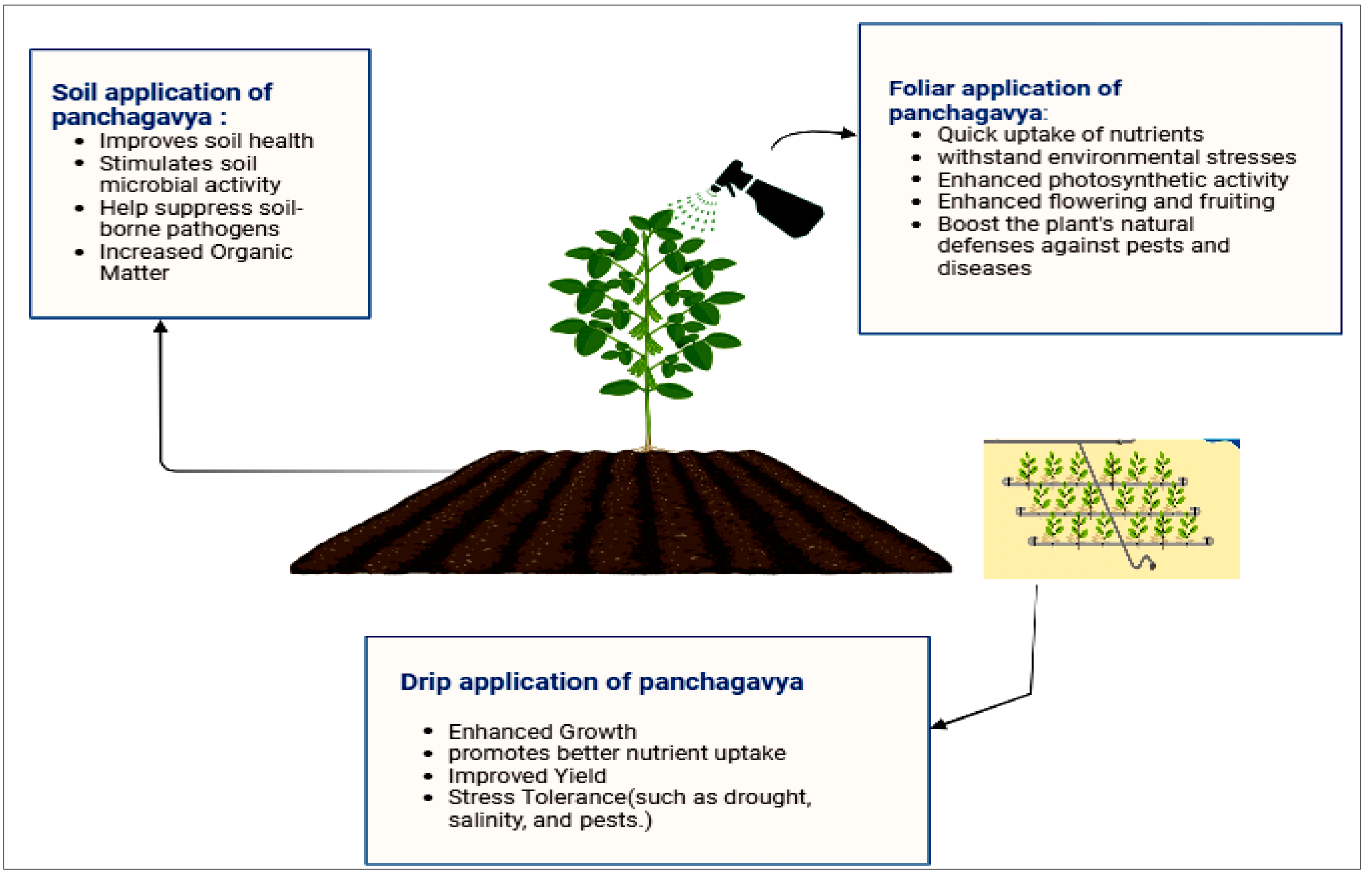

Fig. 4. Different application methods of *panchagavya* and their effect.

and growth regulators like auxins and gibberellins as well as beneficial microorganisms like phosphorous-solubilizing bacteria, *Azotobacter* and *Pseudomonas*. *Panchagavya* increases soil health by raising macronutrients, micronutrients and beneficial microbes, all of which enhance soil fertility (14). *Panchagavya*-sprayed plants usually develop denser canopy and larger leaves (Table 1). It combats diseases and pests. Various beneficial metabolites produced by microorganisms such as organic acids, hydrogen peroxide and antibiotics are effective against variouspathogenic microorganisms (15). According to a study, the highest levels of N, P, K, S, Zn and Fe content and uptake in both seed and straw as well as protein content in black gram seeds, were found when *panchagavya* was applied during both the branching and flowering stages (16). This contrasts with the application of *panchagavya* at either the branching or flowering stage alone, where the observed levels were comparatively lower. A study concluded that the main characteristic of *panchagavya* is its ability to bring all crops' output levels back to normal when the land is switched from an inorganic to an organic culturefrom the first year onward (11). For every crop, the harvest is advanced by 15 days. It extends the shelf life of fruits, cereals and vegetables and enhances their flavour.

Table 1. Effect of *panchagavya* on different crops.

Crop	***Panchagavya* effect on growth**
Rice	The application of *panchagavya* may be able to reduce crop salinity stress and increase the fertility of salt-affected soil (104).
Sweet corn	Adding farmyard manure at a rate of 10 t/ha together with 50 % RDF and 3 % *panchagavya* (foliar spray) to sweet corn is a practical and cost-effective wayto increase crop yield (105).
Pearl millet	To achieve higher yield and net returns, summer pearl millet should befertilized with 75 % RDN with foliar spray of *panchagavya* at 4 % and 500 L of *jeevamrutha* per ha with irrigation at 30 and 45 DAS (106).
Chickpea	The application of liquid organic manure spray to 3 % of the pod countresulted in a considerably greater haulm yield, comparable to that of 10 % vermiwash and 10 % cow urine (107).
Pigeon pea	In comparison to other treatments, there were more total culturable bacteria (47×10^{8} cfu g^{-1}), actinomycetes (32×10^{5} cfu g^{-1}) and fungus (14×10^{4} cfu g^{-1})in the soil rhizosphere when seeds were treated with *panchagavya*. When seedlings were treated with *panchagavya*, their root length rose considerably (108).
Cowpea	Plant height, increased yields of dry matter and green fodder, net return and the B:C ratio of fodder cowpea may all be achieved by applying a 2 %foliar spray of *panchagavya* at 20 days intervals (109).
Blackgram and Greengram	When compared to banyan tree soil, vermiwash and *jeevamrutha*, the use of *panchagavya* at 3 % as a foliar spray at 15, 25 and 40 days after sowing onblack gram and green gram produced the maximum seed production (18).
Groundnut	Applying 4 % *panchagavya* spray, 500 l/ha of *jeevamrutha* in the soil throughout the branching and blooming stages, and 5 t FYM/ha were determined to be the most efficient and economical methods for achieving a greater pod yield (110).
Field mustard	10 % Sanjibani and 3 % *panchagavya* were not noteworthy.For both treatments, (10 % Sanjibani and 3 % *panchagavya*) The characters' means, such as the quantity of siliqua plant^{-1}, the number of seeds siliqua^{-1} and the seed yield plant^{-1}, were discovered to be much greater than the control (111).
Tomato	3 % *panchagavya* was the most effective treatment regarding the growth and yield characteristics of tomatoes (112).
Okra	*Panchagavya* 3 % spray showed higher photosynthetic pigments, such as chlorophyll A, chlorophyll B and carotenoid and showed better results such as the number of fruits 19 and fruit weight (30.67 mg/fruit), were found. It was found to be higher in the 3 % *panchagavya* spray and lower in the control and other concentrations (113).

Shelf life has a wide range within liquid formulations. *Panchagavya*, among these liquid formulations, stands out as a crucial candidate for shelf-life studies (17). Its significance lies in its proven effectiveness for crop growth and its widespread use among farmers. Foliar sprays containing *panchagavya* enhance the physiological growth, yield, yield characteristics, economics, chlorophyll content, dry matter production and yield of black gram (18). A greater rhizosphere microbial population was seen with *panchagavya* spray and *panchagavya* seed treatment, followed by *panchagavya* and *beejamrutha* seed treatment in maize crops (19).

Panchagavya's impact on seed germination and soil quality revealed several adverse effects on plants. Higher concentrations hindered seed germination and reduced root and shoot length, suggesting an inhibitory effect on plant growth. Additionally, water-soluble micronutrients like Cu, found in *panchagavya*, negatively affected seed germination and could be detrimental to plant growth. The presence of trace elements like Cu was also toxic to plant roots, impairing root growth (20). Although *panchagavya* increased soil respiration due to heightened microbial activity, excessive application risked upsetting soil microbial balance, which could impact nutrient cycling and soil health. Therefore, while *panchagavya* offers benefits, moderation in its use is crucial to avoid these negative impacts, emphasizing the need for careful dosage and application methods to capitalize on its advantages without harming plants or soil (21). Traditional *panchagavya* did not have a clear stimulatory effect on the enzymes of ammonia assimilation, such as glutamine synthetase, glutamate synthase and glutamate dehydrogenase, in contrast to seaweed-based *panchagavya* (22).

Smart automation for *panchagavya* preparation was studied (23) and presented the results of the pilot-scaledevelopment of the ATmega 328 microcontroller-based automated *panchagavya* natural fertilizer preparation prototype, along with drip irrigation. The results demonstrate that *panchagavya* made using the automated technique is superior to the traditional method. If this approach is used, the application of the naturally decliningfertilizer *panchagavya* may be made more widely known, which would greatly benefit the agriculture industry and increase production economically.

Dasagavya

Natrajan has furtherimproved the formulation to make it suitable for a range of agricultural and horticulture crops. It is referred to asenhanced *panchagavya* (*dasagavya*). This indigenous nutrition solution is based on cow extract. To prepare enhanced *panchagavya*, 5-9 components are needed: tender coconut, banana, water, jaggery, cow dung, cow urine, cow milk and curd from cow milk. These work like magic when combined and applied properly (24). Under 3 % *dasagavya* + 5 t/ha FYM, wheat grain yield was much greater (48.63 q/ha) (25).

Jeevamrutha

Jeevamrutha is a modest shade of green with a faint, disagreeable smell. It takes on a deeper colour and more potent smell as the storage time goes on. The Sanskrit terms Jeeva, which means 'living being,' and Amrutham, which means 'elixir' or 'medicine to prolong life,' are combined to form the name *jeevamrutha*. *Jeevamrutha* is used in agriculture to encourage crop development (7). The complex microbial bioformulation known as *jeevamrutha* is utilised in traditional Indian organic agriculture and is made from locally available resources such as soil, water, pulse flour, jaggery, cow dung and urine (26).

Jeevamrutha should be given between 9-12 days after preparation. The results of the microbiological research showed that the population of bacteria was higher than that of N-fixers, P-solubilizers, fungi and actinomycetes (27). The increased beneficial microbial load would mobilizemore plant nutrients and supply compounds that promote plant growth in addition to other micronutrients that theplant needs. The application of *jeevamrutha* led to enhanced growth and yield-related parameters in tomatoes. The increased production was attributable to the gradual release of nutrients during the crop's growth period as well as the enhancement of the soil's physical, chemical and mineralogical properties, which improved its fertilitystatus (28). The study suggested that applying a 5 % *jeevamrutha* solution via foliar spraying at 20, 40 and 60 days after sowing (DAS) could lead to increased maizegrain yield (29). *Jeevamrutha* is a miraculous microbiological culture. Introducing *jeevamrutha* with irrigation water activates beneficial soil microorganisms, including earthworms. The abundance of bacteria in the soil promotes microbial activity. Applying *jeevamrutha* at a low rate not only improves soil health but also functions as a tonic.*Jeevamrutha* is typically sprayed as a foliar spray at a rate of 500 L/ha. Applying *jeevamrutha* improves crop nutrient availability and absorption (24). Highest plant height (114.70 cm), leaf area index (6.14), number of panicles (396), number of filled grains/panicle (102.67), grain yield (5752 kg/ha), and straw production (7953 kg/ha) were all recorded with RDF + *jeevamrutha* at a 3 % rate (30).

Jeevamrutha has a greater concentration of microorganisms. The presence of these advantageous microbes in these liquid manures is mostly attributable to their constituents, which include jaggery, gramme flour, cow dung and urine. It also includes vital macro and micronutrients, vitamins, amino acids and growth-promoting agents such as gibberlic acid (GA) and indole acetic acid (IAA) as well as advantageous microbes. When soil is introduced during *jeevamrutha* preparation, it acts as an inoculum of bacteria, fungus and actinomycetes. Therefore, these organic manures are used in agriculture and would act as a complement to various biofertilizersand biocontrol agents. The soil bacteria in liquid manures transform disease-causing soil into disease-restrictive soil by secreting proteins, organic acids and antioxidants with organic matter and converting them into energy (26, 27).

Kunapajala

The history of *kunapajala*, a liquid organic manure, may be traced back to manuscripts from the year 1000 AD, including the Vrikshayurveda and Lokopakara (31). Additionally, information on '*Kunapajala*' can be found in 'Upavanavinoda', an anthropological compilation titled 'Sharangadhara Paddhati' that was put together in the thirteenth century by Acharya Sharangadhara. 'Kunapa' is Sanskrit for 'smelling like a dead corpse or putrid'. Kunapambu, also known as *kunapajala*, got its name from the fact that it involved fermenting animal remains including flesh and bone marrow, which gave off an unpleasant smell (32).

Being a traditional organic liquid formulation, *kunapajala* can sustainably increase agricultural productivityby restoring soil health that has been damaged by chemical application, enhancing the physical, chemical and biological properties of the soil and offering a variety of nutrients, growth-promoting hormones, enzymes, vitamins and other elements as mentioned by (33). Valmiki continued his experimentation with *kunapajala* in Arunachal Pradesh in Northeast India (34) and developed 'herbal *kunapa*' and called it *Sasyagavya.*

According to an analysis of *kunapajala*'s physical and chemical characteristics (35) it is rich in a variety of nutrients. It can be sprayed directly into the soil, used as a foliar spray orused as a seed treatment or primer. In addition to adding nutritious value, the various substances utilised to make*kunapajala* also guarantee bio-pesticidal qualities. For example, adding rice husk to *kunapajala* increases the formulation's silica content, strengthening the plants' defences against insect and disease assaults (33). In black gram cultivation (36), observed that treatments utilizing *kunapajala* at concentrations of 5 % and 10 % yielded superior results, additionally *kunapajala*, at a concentration of 3 %, consistently demonstrated better performance across various growth characteristics. It was mentioned that for the crop and soil, *kunaapajala* should be used after 20 days of preparation so that we may fully use its potential (37). *Kunapajala* contains a healthy microbial community and a high nutritional content. *Kunapajala*'s microbial community has a significant impact on its nutrient makeup fungi break down complex organics for plants. While Phosphorous Solubilizing Bacteria (PSB) increases phosphorus, nitrogen-fixing bacteria increase nitrogen. *Pseudomonas*, *Trichoderma* and other actinomycetes break down organic materials and shield crops from disease. *Kunapajala* can be utilized to its fullest potential by soil and crop fromthe very beginning of its preparation until up to 40 days after its completion. Effect of vegetarian *kunapajala* in rice that utilizing *kunapajala* (3 %) as a foliar spray in a mixture of water and cow urine (9:1), combined with *kunapajala* (10 %) as a soil treatment, led to significant improvements in various outcomes, such as plant height, carotenoid levels, soluble protein content and total chlorophyll concentration (38). When compared to conventionally applied solid organic manure, *kunapajala*'s liquid condition allows for a better absorption rate by plants. Compared to NPK fertilizers, *kunapajala* has demonstrated increased levels of fibre, ascorbic acid, carbohydrates, total solids, lycopene, carotenoids, proline and soluble proteins (28). The tomato plants that were fed liquid organic manure (*kunapajala*) had the greatest antioxidant content (39). In herbal formulations, the amounts of primary nutrients were 1.09 %, 0.10 % and 0.33 % respectively; innon-herbal formulations, the corresponding values were 1.29 %, 0.12 % and 0.43 % for N, P andK (40). According to a study, Vrikshayurveda has precisely systematized agricultural practices that advise using decomposed materials like ash or animal waste in liquid forms, *panchagavya* and liquid organic fertilizers like "*kunapajala*" to improve the biological effectiveness of soil,crops and the production of vegetable and fruit crops (41).

While the study (42) on fermented bio-extracts and cowpea growth in Northeast Thailand didn't explicitly mention negative effects, it's crucial to acknowledge that despite their potential benefits for plant growth and yield, bio-extracts can pose risks if not utilized properly. These risks include nutrient imbalances, soil salinity from salt-rich extracts, phytotoxicity, disruptions to soil microbial balance and environmental contamination from improper disposal. Adhering to recommended application rates, understanding the extract composition and considering plant and soil needs are vital to mitigate these potential drawbacks and optimize the benefits of bio-extracts.

Modified kunapajala

In contrast to non-vegetarian *kunapajala* made in the past, Nene invented a method for making vegetarian *kunapajala* without sacrificing its nutritional content. Soybean meal, paneer, tofu, rice husk, black gram,groundnut oilcake, cow dung, cow urine, honey, clarified butter and milk were used to make vegetarian *kunapajala*. Presence of several phytochemical substances, on the 20th day of fermentation, hexanoic acid constituted 27.49 %, along with the identification of phenol-TMS, methyl oleate, octadecanoic acid (5.72 %) and tetradecanoic acid (2.89 %). Notably, by the 40th day, hexanoic acid, caproic acid and n-caproicacid (22.79 %) exhibited the highest peak area, followed by butylated hydroxytoluene (27.24 %). As the fermentation period extended to the 60th day, butylated hydroxytoluene or phenol, 2,6-bis (1,1-dimethylethyl)- 4-methyl reached the highest %, recording 37.02 %. These substances are essential for physiological reactions, insect repellent, antifungal, antibacterial and anti-fertility properties. Enhanced iron and zinc content, greater grain and stover yield and improved iron and zinc content were the outcomes of foliar spraying *kunapajala* + cow's urine 5:1 at 3 % + organic nutrient source (ONS) of iron at 5 % + ONS of zinc at 5 % (32).

Fermented fish extract

Fermented fish extract (FFE) is one of the organic formulations used to enhance crop development and growth. Brown sugar is combined with fish waste, which is then allowed to ferment. It includes a variety of minerals and amino acids it is crucial for the growth of both plants and microbes. FFE is utilized as a nitrogen source to enhance growth and size during the early, or vegetative, stage of development (43, 44).

Gunapaselam, a fermented fish waste, has been shown to positively affect the xylem and phloem vessel's conducting abilities and replenish the soil with nutrients needed for plant growth. Consequently, *gunapaselam* could be utilized as an effective organic liquid fertilizer to increase crop output at a lower cost and without the negative impacts of chemical fertilizers (45). The application of organic fertilizers, such as fermented fish waste, has a significant impact on leaves, which are an important physiological factor in *Vigna radiata* growth and yield (46).

Fish waste may be utilized to produce mungbean plants in an efficientand nutrient-rich manner as organic liquid manure. It was discovered to include a sizable quantity of vital plant nutrients, including calcium, magnesium, phosphorus, potassium and nitrogen (47). Mungbean field verified that applying a foliar spray containing 2.0 % fermented fish waste extract enhanced the plant's growth, yield characteristics and grain production. Spraying of FFE increased the 20 % yield and 4 % of the protein as obtained from tests (48). Applying 1 % FFA foliar resulted in an 18.4 % increase in green leaf vegetable output compared to the control. This may be because the FFE's supply of macro- and micronutrients as well as growth hormones enhanced the growth characteristics of the plants, resulting in higher plant height, more leaves and higher chlorophyll content, all of which raised the production of green leaves (47). Under sodicsoil conditions, the different physiological parameters and rice production were greatly impacted by the application of fish amino acid or FEE foliar spray in conjunction with the acceptable dosage of fertilizers (49).

Potential use of trash fish manures in agricultural fields. Nutrients and minerals were analyzed in trash fish samples. High amounts of nitrogen (6 %), phosphorous (5 %) and potassium (4 %) were present in trash fish and used for plant growth studies (50). A study concluded that field experiments on mungbean confirmed that foliar spray of 2.0 % fermented fish waste extract increased the growth, yield parameters and grain yield of mungbean (51). Increased FFE dosages decreased amaranthus's output of green leaves. Under 4 % FFE, the lowest yield of 0.91 t/ha was observed (47). Fermented fish waste contains critical amino acids such as arginine, threonine, valine, isoleucine, methionine, leucine, lysine and tryptophan. The well-balanced form of around 16–18 amino acids found in fish protein is produced by microbial proteolysis (52). In mungbean, foliar spraying 2.0 % Fermented fish waste extract produced noticeably more pods per plant (28.3) and seeds per pod (9.9) than 0.5 % fermented fish waste extract (FFWE) (51). The beneficial effects of fermented fish waste extract can be attributed to its fermentation-processed components, the proteins and basic low molecular weight compounds are produced by the breakdown of lipids, carbohydrates, etc. Consequently, plants may access nutrients from the fermented fish waste extract more quickly than from the conventionally applied organic matter(53-55).

Fermented egg extract

One kind of organic fertilizer derived from eggs is called fermented egg extract (FEE). The process is letting eggs ferment in water to extract the proteins, amino acids and other nutrients found in the egg whites and shells. The resultant solution is then diluted and applied to plants as a foliar spray or soil drench to supply vital nutrients. In organic farming, a liquid fertilizer made from eggs is referred to as FEE (56). It is made by fermenting entire eggs along with water and sugar. Numerous minerals, enzymes and amino acids that can aid in plant growth can be found in the resultant solution. Essential amino acids like lysine, methionine and tryptophan are found in FEEs, along with non-essential amino acids like glutamic acid and alanine. These amino acids are necessary building ingredients that plants need to synthesize proteins. FEEs can also include vitamins (like B vitamins) and minerals(such as calcium and phosphorus) that are obtained from the egg and the fermentation process (57).

The preparation of FEE is as follows. A plastic container was filled with the juice extracted from twenty fully ripe lemons. 10 eggs were then placed in the lemon juice and left for 10 days, or until they were thoroughlysaturated. The eggs were well mashed after ten days and 250 g of jaggery was added. This mixture was then stored for ten days. After ten days, the substance was filtered and the liquid part was taken out and put away in adifferent container for foliar spray (58).

Enhancing the rapid absorption and assimilation of nitrogen, phosphorus, potassium and micronutrients from FEE and fish amino acid through the foliar spray at 15, 30 and 45 days after sowing (DAS) would have enhanced the plant's height, leaf count and chlorophyll content through greater metabolic activity and cell division. This has raised the plant's photosynthetic activity, which in turn produced more green gram yield (56). Essential amino acids like lysine, methionine and tryptophan are found in FEEs, along with non-essential aminoacids like glutamic acid and alanine. These amino acids are necessary building ingredients that plants need to synthesise proteins. FEEs can also include vitamins (like B vitamins) and minerals (such as calcium and phosphorus) that are obtained from the egg and the fermentation process, influencing metabolic activity and cell division. This, in turn, may have led to increased plant height, a greater number of leaves, elevated chlorophyll content and enhanced photosynthetic activity. These improvements likely contributed to enhanced yield attributesand a higher grain yield in green gram (49). Egg lemon juice extract and fermented weed extract of the weed, *setaria italica* were effective in controlling leaf blight disease of amaranthus (58). Tomato plants treated with *panchakavya* and egg lime mix had higher fruit weights (34.2 g fruit^{-1}) than the control (22.0 g fruit^{-1}). Larger leaves and a denser canopy emerged when the plants were sprayed with amixture of egg lime and *panchakavya*. The stem developed more robust branches and lateral shoots and its extensive and thick roots allowed for greater nutrition and water absorption. The application of the prescribed fertilizer dose in combination with a foliar spray containing 1.0 % FEE produced a considerably greater soluble protein level of 27.3 % compared to the recommended fertilizer dose used alone. The delivery of more nutrients, particularly nitrogen and micronutrients, to the developing tissues, may be the cause of the relative increase in soluble protein content, which facilitated the synthesis of soluble protein (49, 56).

Vermiwash

Vermiwash is beneficial for agricultural productivity because of its richness in various minerals and compounds. The following are vital minerals and nutrients found in vermiwash: micronutrients and soluble plant nutrients suchas nitrogen (N), potassium (K), phosphorus (P) and calcium (Ca). Mucus from earthworms, growth hormones, organic acids and enzymes. vitamins, enzyme combinations, different amino acids and hormones like auxins and cytokinin. In addition to fungi and heterotrophic bacteria, beneficial microorganisms include phosphate solubilizers, actinomycetes, nitrogen-fixing bacteria and other microbes, which are both, the derivatives of amino acids and themselves, environmentally acceptable, non-toxic materials that protect plants from bacteria (59).

Vermiwash, being high in essential nutrients and advantageous microbes, improves the uptake of nutrients by plants, leading to increased yield (60). Vermiwash, a blend of various animal, agricultural and culinary wastes, is a valuable bioproduct that can be sprayed on the leaves of paddy, maize and millet crops to promote early blooming and significant growth and productivity (59). The biofertilizer potential of vermiwash is due to its growth-promoting characteristics, which emulate gibberellic acid and yield effects surpassing those of gibberellic acid. This suggests that vermiwash holds promise as a biofertilizer for improving germination and seedling growth metrics in pulse crops (61). In addition, it decreased fruit deformity and increased photosynthetic efficiency. Vermiwash is an effective natural plant growth booster (62). Vermiwash outperforms vermicompost in terms of phosphorus, calcium, magnesium and sodium, but they exhibit differences in pH, conductivity and nutrient content (50). Due to the presence of substances that encourage plant development, such as auxins, cytokinins and gibberellins, vermiwash and vermicompost showed improved nutritional quality (63). The essential nutrients, nitrogen (N), phosphorous (P) and potassium (K) are abundant in vermiwash, a liquid biofertilizer (59, 64). Vermiwash appears to have an innate ability that serve as a moderate biopesticide in addition to being a liquid organic biofertilizer that encourages plantdevelopment and production (65).

Effective microorganism (EM)

Teruo Higa, during the 1970s, created this for natural or organic agricultural systems. This microbial solution has since been used to address other environmentalproblems and make it easier to utilize the majority of waste (66). The EM consists of diverse cultures of naturally occurring microorganisms that, when applied as inoculants, enhance the microbial diversity of soil, plants, livestock and ecosystems, promoting sustainable performance. Extensively documented for their capacity to enhance soil quality as well as the growth and yield of crops, EM comprises a myriad of microbial species (67). The prevalent populations within EM include lactic acid bacteria, yeasts, actinomycetes and photosynthetic bacteria. Given that the majority of microorganisms in EM cultures are heterotrophic, relying on organic sources of carbon and nitrogen, the optimal effectiveness of EM is observed when applied in conjunction with organic amendments. This combination ensures the provision of essential carbon, nitrogen and energy for the microorganisms (68).

The EM is utilized as foliar fertilizers in modern agriculture to provide safe and high-quality food (69). The use of EM, which was created with fruit waste and other organic materials, in the treatment ofsewage water shows promise in both significantly lowering the pollutant load and economically achieving the required criteria for sewage water for use in field irrigation (70).

Compost tea

Compost tea is made by pouring recirculated water over a porous bag of compost that is suspended over an open tank to preserve aerobic conditions. The result of this process is also known as organic tea and aerated compost tea (71). A vast variety of bacteria, fungi, protozoa and nematodes are addedby compost and compost tea. Generally, compost that has been properly prepared contains helpful microbes. Making or getting high-quality compost is so essential. The plants should be foliar applied with 5-gal ac^{-1} of excellent, as-fungal-as-possible tea at the first true leaf stage, then again immediately before and soon after flowering. If the fungal component is too low the number of gallons of tea should be increased (72). The main reason for compost tea application is more popular than compost application is that the composts function more slowly over extended periods and require considerably bigger amounts. The effects of compost tea wear off quickly, thus repeated applications or frequent ones are needed to restock the soil or plant surface with nutrients and/or beneficial microbes (73). Applying compost tea as a foliar application enhances the availability and absorption of nutrients, enhancing the microbial activity-induced turnover of nutrients and organic materials in the soil. PGRs, humic acid and other bio-stimulatory substances found in compost teas have stimulatory effects on plants (74).

The greatest substitute source of liquid organic nutrients for use in agriculture and horticulture is compost tea. Humic acids and antagonists are additives that increase suppressivity and extend their range of action. Growing usage of CT might decrease agricultural waste, use less mineral fertilizers, plant fungicides and soil fumigation, increase the quality and productivity of the horticulture supply chain and enhance the integration of the outcomes into commercial agricultural production systems. Compost tea is a good substitute for synthetic fertilizers (75).

Smoke water

Fire is a common method used in both developed and developing nations to get rid of agricultural leftovers. This practice is now known as prescribed burning. While this method is practical and economical, there are several risks associated with it such as air pollution and the eradication of helpful soil microbes. In areas where there is a risk of wildfire, the smoke from the fire helps seeds germinate. As a result, plant-derived smoke and its aqueous extracts have a wide range of uses as components in agriculture (76).

As per reports, smoke has a significant impact on several plant biology processes, including flowering, plant development and seed germination. Numerous chemicals, including hydroxybenzenes, alcohols, lactones, aldehydes, acids and ketones, are found in smoke. From smoke created by plants, a physiologically active butanolide was isolated (77). It is suggested that the mode of action of smoke -water or butenolide is similar to plant growth hormones (78). Karrikins are a chemically defined family of plant growth regulators discovered in smoke from burning plant material (79).

When okra seedlings were sprayed with smoke water their shoot and root lengths (157 and 184 mm respectively) were considerably longer than those of the control seedlings (145 and 133 mm respectively) Foliar treatments of smoke water had a good influence on the growth of okra and tomato seedlings. In the case of tomato seedlings, the application of smoke-water raised shoot and root lengths (107 and 186 mm respectively) substantially when compared with the control. Vegetable seedling vigour was markedly increased by treating tomato, okra and bean seeds with smoke water and a butenolide that was isolated from smoke (80).

Pink-pigmented facultative methylotrophs (PPFM)

PPFMs are recognized for enhancing plant growth through various mechanisms, including nitrogen fixation and nodule formation, phosphate solubilization, production of plant growth regulators such as auxins, cytokinin and gibberellic acid, synthesis of urease enzyme, vitamin B12 production and the synthesis of siderophores. PPFMs contribute to a diverse range of beneficial effects on plants, including hastening seed germination and seedling growth, promoting accelerated vegetative growth through the production of phytohormones, increasing leaf area index and chlorophyll content, facilitating earlier flowering, fruit set and maturation, improving fruit quality, colour and seed weight and enhancing overall yield by 10 %. Additionally, PPFMs play a role in mitigating drought stress (81). The application of PPFM spray triggers the production of diverse enzymatic (superoxide dismutase, catalase, ascorbate peroxidase and glutathione reductase) and non-enzymatic (cysteine, glutathione and ascorbic acid) elements within plants, offering protection against Reactive Oxygen Species (ROS) and consequently alleviating the impact of drought stress on the plant (82).

Applying PPFM 38 (p5m2) as a seed treatment (1 %) followed by foliarapplication (2 %) twice, at 30 and 50 days after sowing, significantly boosted the growth of aerobic rice (83). It was reported that inoculating direct-seeded rice with PPFM isolates and PSB resulted in a significant increase in chlorophyll content (84). Another study reported that 2 % PPFM foliar sprayon tomato at 25 and 45 days after transplanting maintained leaf water potential and leaf temperature under droughtconditions and also reduced flower drop % and increased the fruit yield by 35 % compared to control (85). A study reported that of all the PGRs and PPFM that were tested, the catalase activity of2 % PPFM (5.76), salicylic acid (6.16 µg H_2O_2 g^{-1} min^{-1}) and brassinolide (6.09) was shown to be substantially higher (82). Brassinolide and PPFM were the PGRs and PPFM that had the highest catalase activity,with PPFM (2 %) showing 27 % greater than the control (22.81 %).

Seaweed extract

A natural substance made from different kinds of seaweed or algae is seaweed extract. It is frequently employed in agriculture as a biostimulant to boost resilience to environmental stresses, increase nutrient absorption and promote plant growth. Auxins, gibberellins, cytokinins and amino acids are among the helpful substances found in seaweed extract that support the growth and development of plants (86). Extracts from seaweed are frequently employed as plant biostimulants. Stress tolerance, crop quality and nutrient efficiency can all be improved using seaweed extract (SE). SE possess antibacterial qualities and can elicit certain reactions from plants (87).

The SE when treated at a rate of 0.5 % per ha reduced the adverse effects of drought stress and raised stalk production per hectare by as much as 3.08 mg ha^{-1}. Furthermore, SE promoted the accumulation of stalk sucrose, which raised the industrial grade of the raw material and enhanced sugar output by 3.4 kg mg^{-1} per ha (88). According to a study, the growthand productivity of finger millet were dramatically enhanced by a foliar spray of seaweed extract at a dosage of 0.3%, applied 20, 40 and 60 days after transplanting (DAT) (Ragi) (86). It has been proven thatadding seaweed extract supplementation to the soil may improve the variety of rhizosphere bacteria, which in turnraises soil nutrient levels and improves rice production and quality (89). Applying vegetal and seaweed extract-based biostimulants topically specifically, SE and legume-derived protein hydrolysate (LDPH) boosted plant development and yield (90). In addition to improving plant growth, physiological characteristics and molecular properties, applying low quantities of seaweed extract as a priming treatment has a better ability to increase the amount of bioavailable macro- and micronutrients in plants (91).

Limitations

The efficacy of bio-extracts as standalone fertilizers is often limited due to their typically lower nutritional content and absence of both organic and chemical components. Animal-based extracts tend to perform better than plant-based ones, though their effects can vary depending on the species. Since bio-extracts are not comprehensive solutions, their beneficial effects are most often observed when used in conjunction with organic fertilizers. Moreover, the mechanisms by which bio-extracts promote plant growth remain largely unknown, making it challenging to optimize their use in agricultural practices (42). *Panchagavya* has limitations, including the potential toxicity of trace elements like copper, which can negatively affect seed germination and root growth. Its efficacy varies with concentration, as higher amounts may hinder germination in some crops. Additionally, the presence of phytotoxic substances and variability in microbial activity can complicate its application, necessitating careful management for optimal results (24).

Enrichment of organic liquid formulation

Among the several types of organic fertilizers, foliar application is a relatively new technique in contemporary crop management that entails improving nutrient use efficiency by direct nutrient absorption through plant leaf. Itworks well in situations where there are reduced soil health conditions, such as low or limited availability of soil-applied nutrients, significant nutrient leaching and insufficient root growth because of soil obstruction (92). Coconut husk ash, along with many other micronutrients, is a good source of magnesium, phosphate and potassium. For providing potassium to immature coconut hybrids, coconut husk ash is a great mineral fertilizer demonstrated that the prehydrolyzation of fish waste with *Ananas comosus* and *Carica papaya* fruit waste greatly enhanced the amount of available nutrients, particularly nitrogen, when combined with specific weeds like *Mikania scandens, Tithonia diversifolia, Chromolaena odorat*a and green manure like *Gliricidia sepium* in the creation of liquid organic fertilizers. *Abelmoschus esculantus* grew best with FB1 fertilizer *(T. diversifolia* + *M. scandens* + *C. odorata* + *G. sepium* + topsoil + coconut husk ash + fish waste + aqueous extract of *C. papaya*), where the fish waste processed with papain produced the highest nutritional content (93). Fish hydrolysate was found to be beneficial for *Vigna unguiculata* (cowpea) and *Capsicum annum* (chilli), at 10 % and 5 % respectively. Fish wastecan be converted into organic biofertilizer, which could be a productive, cutting-edge and environmentally responsible way to address both the negative agricultural effects of using chemical fertilizers and environmental concerns (94). *T. diversifolia*, *M. scandens* and *C. odorata* have been shown to have the potential for use in the production of organic fertilizers, which would provide an inexpensive method of controlling these weeds (93). A study revealed that without using potassium 40 % *C. odorata* + 50 % coconut fibre + 10 % activators fertilizer increased grain yield at tropical upland rice by up to 29 % and nutrient uptake of N, P and potassium(95). Spinach leaves and height are greatly influenced by the liquid organic fertilizer made from peanut and banana peels. To achieve exceptional height andleave quantities of spinach, the optimal dose for liquid organic fertilizer provision is 50 mL of liquid organicfertilizer made from peanut peels plus 50 mL of liquid organic fertilizer made from banana peels (96).

By adding fulvic acid to the soil and spraying it with seaweed extract at a concentration of 3 g/L, the highest fruityield/m^2, fruit number/plant, total sugars, total soluble solids (TSS) and carotenoids were achieved. Additionally, the highest values of cytokines, P, K, Fe and total carbohydrates were found in the leaves. EM, yeast extract and seaweed extract may all be used to address the sweet pepper fruit's high growth, mineral levels, enzymatic activity,fruit output and nutritional value (97).

Phosphorus availability is influenced by its chemical forms, soil pH and interactions with soil particles, leading to challenges in maintaining its bioavailability for plants. Biological processes and environmental factors further complicate its availability, necessitating innovative recovery strategies. Given these complexities, strategies for recovering and reusing phosphorus, such as those employing novel sorbents are deemed essential for sustainable nutrient management. These sorbents are designed to efficiently capture phosphorus from waste streams, like sludge water and release it in a form more available for plant uptake. The financial viability and environmental benefits of such approaches highlight their potential for addressing phosphorus availability challenges in agriculture (98). Waste management is evolving into waste valorisation, with biological and chemical refining methods leading the way. Key technologies with high economic potential include insect rearing for cleansing products and feed, phosphorus and nitrogen regeneration for fertilizers and pyrolysis for cement substitutes. These approaches emphasize sustainability and circularity in waste management (99). Biochar is gaining prominence in sustainable agriculture for its ability to enhance soil health, improve nutrient retention and sequester carbon, thereby supporting climate change mitigation. As a natural soil amendment, it boosts microbial activity and water retention, and reduces reliance on chemical fertilizers, aligning with organic farming principles. This makes biochar a valuable tool for increasing crop yields and advancing environmental sustainability (100). Synthesis of silica nanoparticles using lignin as a soft template, extracted from coir pith, nano silica can improve the absorption of essential nutrients in plants, leading to better growth and yield. It helps crops withstand abiotic stresses such as drought and salinity, promoting overall plant health and productivity (101).

AI-based predictive maintenance in the Industrial Internet of Things has shown substantial potential in reducing operational costs and improving system reliability. Moreover, the use of AI in monitoring and adjusting agricultural inputs can lead to more sustainable practices, reducing the reliance on finite resources while maintaining economic viability (102). Fossil fuel prices are a critical determinant of the economic sustainability of agricultural practices. As fossil fuels are integral to the production and transportation of agricultural inputs, any fluctuation in their prices directly impacts the cost-effectiveness of these inputs. For instance, as discussed by (103), the international price of oil influences the cost of fertilizer production, thereby affecting the overall profitability of crop production. In light of this, the development of bio-based alternatives offers a strategic advantage, potentially insulating the agricultural sector from volatile fossil fuel markets.

A diverse array of inputs exists for the formulation of organic liquid fertilizer, encompassing cow products, animal waste, plant waste and fruit waste. These materials boost substantial nutrient content, rendering them suitable forpractical application in agriculture. Organic liquid fertilizers have the potential to serve as a viable supplement toplant nutrient needs, thereby fostering sustainable agricultural practices.

Conclusion

Liquid organic fertilizers offer a wide array of options for agricultural use, featuring a rich blend of macro and micronutrients, amino acids and beneficial microbes. Their application via foliar spraying presents an environmentally friendly, cost-effective method that promotes soil and plant health while maintaining nutrient balance. These fertilizers play a pivotal role in organic farming, fostering enhanced crop growth, development and ultimately, higher productivity accompanied by superior quality. The nutrient composition of organic liquid formulations can vary depending on the raw materials used and the duration of fermentation. Combinations of these products may exhibit synergistic effects, further augmenting crop performance and yield. By harnessing these formulations, agricultural waste materials can be repurposed as valuable resources for nutrient management in organic farming, thereby contributing to the advancement of sustainable agriculture practices. Further investigation into the combined effects of different formulations is warranted to scientifically ascertain their ability to enhance nutrient content and bolster microbial populations. Additional research is imperative to explore the efficacy of these formulations and expand the range of options available in organic liquid fertilizers. The production costs of these bio-extracts are estimated to be cost-effective, which is competitive when compared to conventional alternatives. However, for widespread adoption, further reductions in production costs are necessary, potentially through innovations in extraction technology or economies of scale, particularly by improving extraction efficiency and exploring alternative sources. Additionally, long-term studies are necessary to assess the sustainability and environmental impact of these practices across diverse agro-climatic regions.

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Authors' contributions

CEM wrote most of the abstract, mechanism of action and conclusion, KR helped in writing the history of formulations and their effect on crops, PE helped in writing materials, methods and result section and in the development of the figure, JP helped in translation, in writing some sections, PG helped in writing some section. All authors read and approved the final manuscript.

Compliance with ethical standards

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