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A CRITICAL REVIEW ON BIO-FORMULATION EFFICACY MECHANISM OF JEEVAMRUTHA-MEDIATED SOIL HEALTH RESTORATION AND CROP RESILIENCE

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ABSTRACT

Jeevamrutha has gained importance in sustainable agricultural practices and environmental management because of its organic bio-formulation. It is prepared using soil, jaggery, pulse flour, cow excreta, which together provide a rich medium for microbial proliferation. Application of Jeevamrutha increases soil nutrients and biological activity and thereby makes essential macronutrients easily available to crops. It supports long-term soil health restoration through improved soil structure, increased organic carbon content, and better moisture retention. Jeevamrutha contributes to plant growth and vigour and enhances the ability of plants to cope with biotic and abiotic stresses through microbial metabolites and enzymes. Jeevamrutha can be used as an alternative to chemical fertilizers as it is cost effective for small and marginal farms. This review critically synthesizes existing literature on the composition, application method, agronomic benefits, and environmental impact in promoting biodiversity, reducing chemical inputs, and supporting sustainable and economically viable agriculture systems.
***Keywords* :** Jeevamrutha; liquid organic biofertilizer; soil microbial diversity; soil health; natural farming systems

Introduction

Utilization of organic biofertilizers has gained importance due to their emphasis on soil fertility restoration along with integration of ecological factors (Bhattacharjee and Uppaluri, 2023). Cow excreta-based biofertilizers are considered promising due to their several properties such as faster decomposition rate, relatively low precursor requirements and high microbial load. Jeevamrutha (JA) is one of the most used organic biofertilizers (liquid or solid form) in rural areas of India. (The bioformulation improves soil microflora and mineral availability through its simple and farmer friendly preparation technique, which in turn fosters an environment that is conducive to nutrient uptake. Thus, the reliance on inorganic fertilizers in agricultural practices can be decreased. Intensive agricultural practices lead to a reduction in soil organic carbon, soil fertility, microbial populations, posing a significant threat to food security (Verhulst *et al.*, 2010). Despite the adverse consequences of chemical-intensive farming, farmers often remain dependent. The difficulty of sustaining or improving agricultural production in an ecofriendly manner has led to several different sustainable agricultural narratives, of which nonchemical or natural farming approaches appear particularly promising. Food crops grown under natural farming systems have a reduced ecological impact, improved soil fertility and better water quality Jeevamrutha, a liquid biodynamic microbial organic formulation, has been used by farmers across India as a low-cost input for improving soil fertility and crop health. The conceptual basis of such fermented organic preparations can be traced to ancient agronomic texts, particularly Vrksayurveda attributed to Surapala (10th - 11th century CE), which describes the use of organic animal and plant-based formulations for enhancing soil vitality and plant growth (Beniwal, 2023).

JA is prepared (illustrated in Figure 1) using 10 L of cow urine, 10 kg of cow dung, 2 kg of pulse flour, 2 kg of jaggery, a handful of undisturbed soil, and 200 L of water. The ingredients are mixed, and the opening of the container is covered with a cloth to permit aeration wile preventing contamination. The mixture is incubated for seven days while being stirred twice a day in a clockwise direction (Palekar, 2006).

Despite numerous efforts, Jeevamrutha has a few shortcomings, including a lack of scientific credibility, storage problems because it is produced and utilized fresh, a lack of performance testing under varied agroclimatic conditions and also a lack of mechanization. Even though several earlier surveys carried out in various Indian states indicated that young farmers were interested in utilizing JA, scepticism regarding its field level efficiency persists. A few research studies have emphasized the impact of JA application on seed germination, crop yield, soil quality, and crop disease management (Gore and Sreenivasa, 2011; Singh and Lal, 2019). However, there is a lack of comprehensive study on the dynamics of microbial composition, metabolites, proteins, and enzymes of JA, as well as their functions in enhancing soil and plant health. Considering these concerns, scientific validation of JA's advantages may boost its legitimacy and acceptance among farmers. A better understanding of the dynamics of microbial populations and physio-chemical characteristics during JA incubation, the correlation of metabolomics, metagenomics, and proteomics of JA to demonstrate functional properties, and the impact of long-term field application of JA on soil health parameters is the aim of this study considering the context.

Composition of Jeevamrutha

The formulation of Jeevamrutha includes six materials namely cow dung, cow urine, water, jaggery, pulse flour, and soil (Fig. 2). Every ingredient in JA has a specific purpose, but together they form a robust means of improving soil nutrition. Cow dung and cow urine shelter several beneficial microorganisms, including *Bacillus* spp., *Pseudomonas* spp., *Azotobacter* spp., *Enterococcus* spp., and actinomycetes, which are well known for their role in plant disease control and provide a scientific basis for the disease suppressive and plant protective effects traditionally attributed to cow-based organic inputs (Girija *et al.,* 2013). Jaggery and pulse flour can each be an additional source of carbon and nitrogen (Radha and Rao, 2014). Likewise, beneficial microbial consortia are introduced through soil as a bio-inoculant. Past studies have targeted JA for field applications and microbiological characterization.

Cow dung is an essential ingredient in the organic formulation and serve as a viable source of beneficial bacteria. Manure from cow dung is abundant in naturally occurring beneficial microorganisms, especially bacteria, yeast, actinomycetes and certain fungi (Swain and Ray, 2009). Gomutra is cow's urine, and studies have reported that it enhances plant resistance against mycoplasma, viruses, bacteria, fungi, nematode, injurious insect. Cow dung and urine, since they are high in amino acids, make Jeevamrutha rich in nitrogen. Jaggery contains approximately thirty percent of the recommended daily intake (RDI) of potassium, which is a high-quality plant nutrient that plants require in large quantities to grow, reproduce and be more resistant to drought. Gram flour is an organic material used in organic formulations because of its high amino acid content. When added, amino acids help beneficial microbes enhance disease resistance and work even in adverse situations.

Chickpea flour, commonly used as a carbon–nitrogen source in JA preparation, provides readily available proteins, amino acids, vitamins (niacin and thiamine), and minerals that support rapid microbial multiplication during fermentation. Banana peels contribute essential macro- (K, P) and micronutrients (Ca, Mn, Na) and decompose rapidly, enhancing nutrient availability in the fermenting medium. Additionally, soil collected from the rhizosphere of mature trees (e.g., banyan) serves as a natural bio-inoculum, introducing beneficial microorganisms such as nitrogen-fixing and phosphate-solubilizing bacteria, thereby enhancing the microbial diversity and functional efficacy of Jeevamrut as a soil bioinoculant (Swain and Ray, 2009; Boye *et al.,* 2010; Esmat *et al.,* 2010; Papen *et al.,* 2002; Sreenivasa *et al.,* 2010).

Biotechnology of Jeevamrutha fermentation

The fermentation process employed in Jeevamrutha facilitates the breakdown lignin, tannic acid and oil from organic plant-based manure, is beneficial for roots development and plants growth. Fermentation of the raw material from which it is made enhances nutrient availability. To obtain the desired moisture content for fermentation of any organic formulation, dry components are mixed with high moisture additives under aerobic conditions, as aeration is an important aspect of effective fermentation (Sala *et al.,* 2019) In the beginning, adequate oxygen is needed to start fermentation as low oxygen availability and excess carbon dioxide can have seriously negative effects. To create these ingredients, they are fermented together for approximately seven days. Fermentation helps to break down organic matter and create products that are more readily taken up by plants. The optimum fermentation period may extend up to 40 days depending on the formulation and intended use, as long as associated with greater nutrient availability. In contrast, shorter fermentation period may result in insufficient decomposition of the biofertilizer and limited nutrient release (Oliveira *et al.,* 2017).

Microbial diversity in Jeevamrutha

The microbial population present in Jeevamrutha provides various benefits to soil and plant growth (Table 1). The microbial diversity that is present in a particular Jeevamrutha formulation will depend on the local composition of the ingredients. Many microorganisms associated with Jeevamrutha include the following types (Devakumar *et al.,* 2008)

Bacteria: Beneficial bacteria like *Bacillus spp*., *Pseudomonas spp*., and other nitrogen-fixing bacteria are present in JA. These bacteria help in breaking down organic matter, fixing atmospheric nitrogen, and releasing nutrients for plant uptake.

Fungi: Microbial diversity includes a range of fungi, especially growth promoting mycorrhizal fungi. Mycorrhizal fungi that form symbiotic relationships with plant roots enhance nutrient uptake. In addition, diseases suppressing fungal components are present in JA, such as *Beauveria bassiana* and *Metarhizium* spp.

Actinomycetes: These are beneficial filamentous bacteria that produce enzymes which contribute to the breakdown of complex organic compounds, making nutrients more available to plants.

Other Microorganisms: Soil health and microbial diversity may be enhanced by the presence of protozoa, nematodes, and other microorganisms. The microorganisms present in Jeevamrutha may help in enhancing soil fertility, boosting crop yield and preventing harmful effects of chemical fertilizers and pesticides. The existence of rich soil fauna in compost contributes to improved soil structure and enhanced water and nutrient availability.

Nutrient composition of Jeevamrutha

Apart from beneficial microbes, Jeevamrutha is a rich source of nutrients that support plant growth and development. The amount of essential macro and micronutrients present in Jeevamrutha is tabulated below (Table 2).

Effect of Jeevamrutha on soil fertility

The major effects of using Jeevamrutha on soil fertility include:

Microbial Diversity: A mixture of beneficial microorganisms including bacteria, fungi and other microbes is present in Jeevamrutha. Once these microorganisms are applied into the soil, they help in the development of a diverse community. Plant roots can act as a shelter for soil microbiomes, and this microbial community can create a barrier against pathogens due to the chemical compounds produced in the root zone (Meena *et al.* 2017).

Nutrient Cycling: The microbes found in Jeevamrutha assist in breaking down organic material present in soil. Essential nutrients are made available to the plants during decomposition. Organic matter provides nitrogen, phosphorus and potassium as it gets decomposed. This process of nutrient recycling leads to improved soil fertility.

Improved Soil Structure: Jeevamrutha is known to improve structure through aggregation which helps in developing pore spaces in the soil. This facilitates improved water penetration and air flow. Improved soil structure helps prevent soil compaction, thereby reducing restrictions on root expansion and water movement.

Suppression of Soil-borne Diseases: A field study reported that soil application of Jeevamrutha significantly reduced the incidence of *Aspergillus niger*, *Rhizopus* sp., *Fusarium* sp., etc in rice and wheat by lowering pathogen population and enhancing antagonistic microbial activity in the rhizosphere (Saharan *et al.* 2023).

Enhanced Plant Growth: The overall effect of improved soil fertility, nutrient availability, and disease suppression results in enhanced plant growth. Plants grown in soil treated with Jeevamrutha are often healthier, more vigorous, and more productive.

Application techniques of Jeevamrutha

The use of Jeevamrutha increases biological activity in the soil. It increases the decomposition of carbonaceous material and releases various plant nutrients. The application of Jeevamrutha improves the fertility and other physical properties of the soil for long-term sustainable agricultural production. Commonly reported application methods of Jeevamrutha include the following:

Soil Application

To apply Jeevamrutha to the soil, it is diluted with water at 1:10 ratio (1 part Jeevamrutha to 10 part water) and put it on the soil directly. This can be done using a watering can or a sprayer. Jeevamrutha has shown positive effects on crops (Palekar, 2006; Vasanthkumar, 2006; Devakumar *et al.,* 2008). The high microbial loads and growth hormones may enhance soil biomass, which presumably assists in the availability and uptake of applied and native soil nutrients further improving crop growth and yield (Boraiah *et al.,* 2017) and enhancing crop yield after harvest. Jeevamrutha has a high number of microbes that rapidly multiply in the soil, it acts as a bio-stimulant to enhance soil microbes (Palekar 2006).

Foliar spray

To use Jeevamrutha for foliar spray, Jeevamrutha is diluted with water in a ratio of 1 : 20. One way to deliver microorganisms and nutrients directly to crop foliage is by spraying. The cob length, cob girth, and hundred grains' weight were significantly higher due to the foliar spray of 5% Jeevamrutha on 20, 40, and 60 DAS in maize. The higher yield attributes may be due to greater photosynthesis and assimilate partitioning from source to sink, along with higher availability of growth stimulating substances (like IAA, GA, cytokinin and kinetin) and essential plant nutrients, which were difficult here (Ramesh *et al.,* 2018). In addition, efficient microorganisms present in Jeevamrutha may co0ntribute to these effects. A research in 2019 in wheat reported that Jeevamrutha foliar at 10% at three week intervals resulted in a better B:C ratio compared to 10% at two week intervals (Kaur and Saini, 2019). Spraying cow urine at 50 percent together with Jeevamrutha (100 percent) has also resulted in significantly higher grain and straw yield of wheat (3066 and 3710 kg/ha) (Behera and Chandrashekara, 2023).

Seed treatment

Before sowing, the seeds can be treated with Jeevamrita solution by dipping or coating. This helps provide essential nutrients and beneficial microorganisms to the emerging seedlings. Jeevamrutha increases the amount of biological activity in the soil, improves nutrients availability to crops, and enhances seed germination (Devakumar *et al.* 2008). Seeds that received Jeevamrutha treatment individually showed the highest germination. Under NaCl stress conditions, seed treated with Jeevamrutha exhibited a significantly higher germination rate (Singh *et al.* 2018).

Combination with organic manures

Using Jeevamrutha with other organic manures stops the physical and chemical ageing of the soil and improves its microbial soil health. Improvement was observed in growth and yield of French beans when combined with FYM which contains nutrients, beneficial microorganisms and growth promoting substances (Kumbar *et al.,* 2015). The Jeevamrutha treatment has enhanced the growth qualities of plants because the nutrients that were solubilized in the soil became available to the crop during the growth stage (Chaithra and Sujith, 2021). Besides nutrients, fermented liquid organic manures also act as carriers of microbial populations, as well as compounds that help in plant growth, better metabolism, and disease and insect resistance (Vurukonda *et al.,* 2024).

Drenching or irrigation

For large areas, Jeevamrutha can be evenly applied as a diluted soil drench or through irrigation systems. Most farmers adopt drip irrigation for applying Jeevamrutha (Kavitha 2023). Jeevamrutha applied via irrigation water in Senna (*Cassia angustifolia* Vahl.) at different rates was evaluated to identify the optimum dosage (Jnanesha *et al.,* 2024). The results confirmed that the application of 150 liters of Jeevamrutha per acre resulted in a noticeable increase in both leaf yield (1,085.2 kg/hectare) and pod yield (318.7 kg/hectare). The highest nitrogen (59.96 kg/ha), phosphorus (14.13 kg/ha) and potassium (43.75 kg/ha) after harvest in marigold cv. Calcutta Orange with Jeevamrutha @ 1000 L/ha applied by drenching around the plant root system (Ashwini *et al.* 2022b).

Crop stage specific application

The frequency and timing of Jeevamrutha application can be modified according to the different growth phases of the plants. It can be applied more frequently during vegetative growth to promote healthy leaf development. The utilization of Jeevamrutha through split application is an important component of nutrient management strategies because a single application of Jeevamrutha causes periods of nutrient oversupply, more losses through leaching or immobilization, as well as phase of nutrient deficiency during critical growth stages. Consequently, soil nutrients may not remain optimum throughout crop growth cycle. For instance, in rice cultivation, split application of Jeevamrutha at tillering and panicle initiation stages has been reported to improve plant vigour, nutrient uptake, and grain yield compared to single time application, owing to sustained nutrient availability during critical phenological stages (Amareswari and Sujathamma, 2014). The beneficial effects of Jeevamrutha are possibly due to the steady supply of plant-available nutrients throughout the growing period, especially at critical growth stages of crops, which leads to improved nutrient uptake, enhanced plant vigour, and improved yield quality attributes (Thejaswini *et al.,* 2022).

Frequency of Jeevamrutha application

Jeevamrutha is usually done once in 2 to 3 weeks, depending upon the requirement of the plants and the soil condition. To determine optimal frequency, regularly monitor growth and health of the crops (Pathak and Ram, 2013). Due to the ingredient quality and fermentation process, a product Jeevamrutha may show variation in its composition as it is a natural product. It is, therefore, a good practice to test its effects on a small area of plants before applying to the whole field. Before applying, proper dilution ratios and application methods must be assured. Overdose application could be harmful to the plants.

Economic and Environmental benefits of Jeevamrutha

Jeevamrutha offers several economic and environmental benefits:

Economic Benefits

Cost effectiveness: JA can be produced on the farm using locally available materials, reducing the need for purchasing expensive synthetic fertilizers, this leads to cost savings for farmers. Previous studies have reported to improved economic returns, with higher cost-benefit ratios compared to synthetic fertilizer used in rice cultivation, primarily due to reduced input costs and comparable yields (Table 3) (Amareswari and Sujathamma 2014).

Increased crop yield: When applied to crops, JA enhances soil fertility and nutrient availability. This, in turn, may lead to increased crop yields, improving the economic return to farmers.

Reduced input costs: By using JA, farmers can decrease their reliance on chemical fertilizers and pesticides, resulting in reduced input costs and potentially higher profit margins.

Improved soil health: JA improves soil health by improving its structure and microbial diversity. Healthy soils require fewer external inputs and have improved water-holding capacity, leading to better crop growth and yield.

Environmental Benefits

Reduced chemical pollution: JA promotes organic farming practices, reducing the use of synthetic fertilizers and pesticides. This leads to decreased chemical runoff into water bodies, minimizing water pollution and its associated negative impacts on aquatic ecosystems.

Enhanced soil benefits: The microbial diversity fostered by Jeevamrutha helps maintain and improve soil health. Healthy soils contribute to better water retention, reduced erosion, and increased carbon sequestration. When incorporating JA into a cropping system, it can provide several benefits (Fig. 3).

Biodiversity preservation: Organic farming methods, including the use of JA, promote biodiversity by avoiding the negative impacts of synthetic chemicals on non-target organisms, thereby supporting beneficial insects, birds, and other wildlife.

Lower Green-house gas emissions: The reduced use of chemical fertilizers and pesticides in JA-based farming can result in lower emissions of greenhouse gases associated with their production and application.

Water conservation: JA enhances water-holding capacity of soil, which in turn reduces the need for excessive irrigation, particularly in regions facing water scarcity or drought conditions.

It is important to note that JA may not perform uniformly across different soil type, climate conditions, crop systems, particularly if application practiced are not optimized. Shifting to organic farming approaches such as JA often requires an adaptation period for farmers.

Community involvement in Jeevamrutha production

Community involvement in JA production can enhance its effectiveness and adaptation. Engaging the communities facilitate knowledge sharing and collective participation in sustainable farming practices. Key community based approaches include:

Knowledge dissemination: Organizing workshops and training sessions can educate farmers and community members about the benefits of JA preparation and application methods. Involvement of subject experts or experienced farmers can strengthen knowledge transfer.

Local sourcing and collaborative production: Encouraging community members to contribute locally available ingredients reduces the cost and promotes resources efficiency. Community led production initiatives can improve operational efficiency through shared labour and collective action. Adaptation of JA formulations based on local conditions can lead to the development of region-specific optimization.

Monitoring and scaling strategies: Establishing systems to monitor crop and soil health to JA application allows communities to evaluate effectiveness. Experience sharing through meetings or online platforms can support continuous improvement.

This could potentially lead to small-scale commercial production, benefiting the community economically.

Jeevamrutha and Organic Certification

Using Jeevamrutha in organic farming aligns with the principles of organic certification, as it emphasizes the use of natural and sustainable practices to enrich soil fertility and promote plant health and growth without relying on synthetic inputs. However, the acceptance of Jeevamrutha as a permissible input may vary based on local organic certification standards and regulations. In India, organic certification is governed under the National Programme for Organic Production (NPOP), implemented by Agricultural and Processed Food Product Export Development Authority (APEDA) through accredited certification agencies. Farmers seeking organic certification should therefore consult their respective NPOP accredited certification bodies to ensure the preparation and use of Jeevamrutha comply with approved input lists, documentation requirements, and regional certification guidelines.

Long-Term Effects of Jeevamrutha on Agroecosystems

Jeevamrutha is considered an excellent reservoir of natural carbon, nitrogen, phosphorus, potassium, and various other essential micronutrients crucial for crops, making it a popular choice for organic farming. Jeevamrutha holds the potential to actively stimulate plant growth and enhance immunity within the plant system. It contributes to the proliferation of earthworms in the soil, providing significant benefits to soil health.

Isolated microbes from Jeevamrutha

Maximum microbial population is reported on the 10th day after preparation in Jeevamrutha. The important microbes isolated from Jeevamrutha are explained below:

Trichoderma spp.

Trichoderma is widely used for managing plant diseases that affect leaves and panicles that are transmitted through the soil. *Trichoderma* can improve the environment by decreasing agrochemical pollution, enhancing plant resistance, promoting plant growth, and improving nutrient utilization efficiency. For several crop species, *Trichoderma spp.* also functions as a safe, affordable, efficient, and environmentally friendly biocontrol agent. For the biological control of plant diseases like potato dry rot, tobacco root rot, melon wilt, crop grey mould, tomato grey mould, cotton *Verticillium* wilt, and other plant diseases, *Trichoderma* has been applied effectively. *T. longibrachiatum* successfully manage the spread of pepper diseases and has a positive impact on pepper anthracnose and damping off (Kim *et al.,* 2023; Pandey *et al.,* 2019).

Numerous *Trichoderma* species in the rhizosphere exhibit the ability to inhabit the root surfaces of both monocotyledonous and dicotyledonous plants, inducing significant alterations in plant metabolism. The colonization process by *Trichoderma* encompasses the identification of the host plant, attachment and penetration into plant roots, and the resistance of *Trichoderma* to metabolites produced by plants as a response to the invasion of foreign organisms, whether pathogenic or non-pathogenic (Tyśkiewicz *et al.,* 2022). Given its broad host plant range, *Trichoderma* likely evolved effective strategies to overcome the defence mechanisms employed by plants. Hence, employing *Trichoderma* for the prevention and management of plant diseases not only hinders the proliferation of pathogenic fungi, promoting plant growth, but also diminishes the reliance on chemical pesticides, thereby fostering the preservation of the ecological environment.

Beauveria bassiana

As per scientific reports, *Beauveria bassiana*, an entomopathogenic fungus (EPF), stands out as the most efficient biological control agent against a diverse array of insect groups. These entomopathogens serve as "biopesticides" or biocontrol agents, offering an alternative to conventional pesticides for crop protection and mitigating the adverse impacts of chemical insecticides on the environment. *Beauveria bassiana* induces white muscardine disease, affecting numerous insects, by weakening the host cuticle through mechanical and chemical forces, eliminating the need for direct ingestion of fungal propagules by insects (Sharma and Sharma, 2021).

Bacillus subtilis

Bacillus subtilis employs a dual biocontrol mechanism involving both direct and indirect approaches. In the direct pathway, the bacterium produces various secondary metabolites, hormones, enzymes that degrade cell walls, and antioxidants, aiding the plant in fortifying itself against pathogenic assaults. The indirect method encompasses the induction of acquired systemic resistance and the promotion of plant growth. Furthermore, *Bacillus subtilis* exhibits the ability to solubilize soil phosphorus, enhance nitrogen fixation, and generate siderophores that facilitate its own growth while impeding pathogenic organisms (Su *et al.,* 2020). The bacterium enhances stress tolerance in its plant hosts by increasing the expression of stress-response genes, phytohormones, and stress-related metabolites. In vitro experiments demonstrated that *Bacillus subtilis* effectively inhibited the growth of *Fusarium oxysporum* (25–34%) and *Botryodiplodia theobromae* (100%), which were isolated from postharvest rots of yam (*Dioscorea rotundata*) tubers.

Comparative study of the effect of Jeevamrutha on different crops

To systematically evaluate the bio-stimulatory potential of Jeevamrutha, a comprehensive comparative study was conducted across an expansive matrix of agricultural systems, encompassing major agronomical, horticultural, floricultural, and oilseed crop varieties. The empirical data synthesized in Table 4 demonstrates that the application of this traditional microbial formulation exerts a profound, statistically significant influence on overall crop performance. Crucially, these positive variations manifest across two primary dimensions: vegetative development and economic yield. On a physiological level, crops treated with Jeevamrutha exhibited enhanced structural growth parameters, such as accelerated canopy development, robust root architecture, and superior biomass accumulation. Simultaneously, from a production standpoint, this heightened vegetative vigor translated directly into optimized harvest indices, improved quality of produce, and elevated net economic returns for farmers. By bridging the gap between biological growth and fiscal viability, these results establish Jeevamrutha as a highly effective, scalable alternative to synthetic inputs across diverse cropping profiles.

Conclusion

Jeevamrutha represents a promising organic bio-input for sustainable agriculture due to its capacity to enhance soil fertility, microbial activity, nutrient availability, and crop performance. Evidence from existing studies indicates that its application can improve soil structure, support beneficial microbial communities, and reduce dependence on synthetic fertilizers and pesticides. However, several limitations remain. Variability in nutrient composition due to differences in raw materials, preparation methods, and fermentation conditions can affect its consistency and field performance. Moreover, limited large scale and long-term field evaluations restrict a comprehensive understanding of its sustained effects on soil health, crop productivity, and agroecosystem stability. Challenges related to standardization, shelf life, scalability, and integration into modern intensive farming systems also need to be addressed. Further research focusing on these constrains, along with the development of optimized application strategies, is essential to maximize its benefits. Exploring the agricultural and environmental benefits of JA aligns with the growing interest in sustainable and regenerative farming practices. Widespread adoption of Jeevamrutha could amplify these benefits and support a greener and more productive agricultural future.

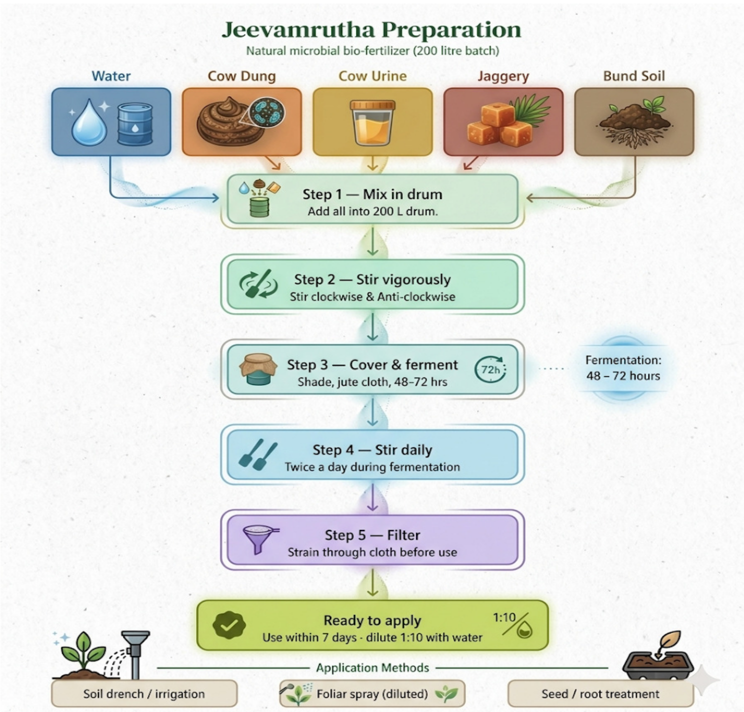

Fig. 1 : Preparation and application of Jeevamrutha

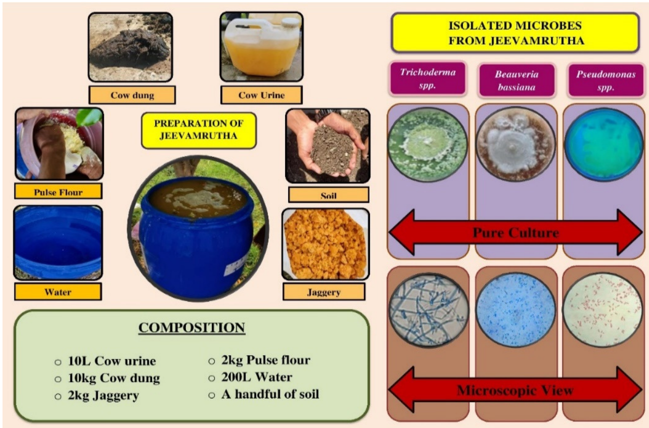

Fig. 2 : Composition, preparation and microbial analysis of Jeevamrutha.

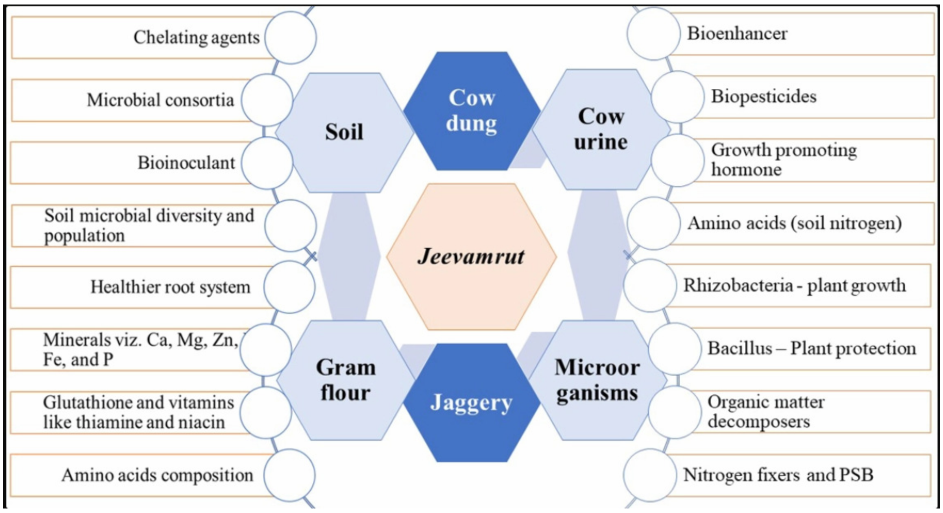

Fig. 3 : Role of Jeevamrutha in Crop Rotation Systems.

Table 1 : Different microorganisms present in Jeevamrutha

Microorganisms	Colony count (cfu/ml)
Bacteria	20.4 x 10^5
Fungi	13.8 x 10^3
Actinomycetes	3.6 x 10^3
Phosphorus solubilizing organisms	4.5 x 10^2
Free living Nitrogen-fixers	5.0 x1 0^2

Source: (https://agritech.tnau.ac.in/org_farm/orgfarm_ofk_soil.html)

Table 2 : Different macronutrients and micronutrients present in Jeevamrutha as per previous characterization (Chakraborty and Sarkar. 2019).

Nutrients	Concentration (ppm or mg/L)
Nitrogen (N)	658 ppm
Phosphorus (P)	195 ppm
Potassium (K)	821 ppm
Calcium (Ca)	189 mg/L
Magnesium (Mg)	19 mg/L
Sulphur (S)	564 mg/L
Zinc (Zn)	1.56 mg/L
Copper (Cu)	2.44 mg/L
Iron (Fe)	42.44 mg/L
Manganese (Mn)	0.394 mg/L

Table 3 : Cost-benefit ratio comparison between Jeevamrutha and synthetic fertilizer (Amareswari and Sujathamma; 2014)

Crop	Treatment	Yield (t/ha)	Benefit - Cost Ratio (BCR)
Rice (Masura)	Jeevamrutha	6.86	3.39
Rice (Masura)	Synthetic fertilizer	7.41	1.09
Rice (Hamsa)	Jeevamrutha	6.50	3.00
Rice (Hamsa)	Synthetic fertilizer	6.17	0.60

Table 4 : Application and effects of Jeevamrutha in different Field and Horticultural Crops

Application rate / concentration	Crop	Major observed effects	Reference
5 - 10%	Rice	Improved soil fertility, higher grain and straw yield, reduced grain ash content	Sharada and Sujathamma 2018
3 - 5%	Maize	Increased plant height, leaf area index, dry matter production, cob size, and grain yield	Ramesh *et al.* 2018
3%	Finger millet	Enhanced plant height, tiller number, leaf area index, grain and straw yield	Aravind *et al.* 2020
500 L/ha	Pearl millet	Maximum plant height, tillers, ear head length and girth, grain and straw yield	Patel *et al.* 2021
25 - 100%	Tomato	Increased plant height, leaf area, branching, root length, and total dry matter	Gopal and Gurusiddappa 2022
2.5%	Black gram	Higher plant height, root length, nutrient uptake (NPK), soil microbial population and dehydrogenase activity	Nitin and Purohit 2021
-	Sweet basil	Increased chlorophyll *a*, chlorophyll *b*, and carotenoid content	Singh and Lal 2019
Ghana: 1250 kg/ha; Dhruva: 3000 L/ha	Groundnut	Improved yield attributes and higher microbial population throughout growth stages	Veeranna *et al.* 2023
500 L/ha	Capsicum	Higher yield compared to other organic manures	Boraiah *et al.* 2017
500 - 1000 L/ha	Cowpea	Increased pods per plant, test weight, and stover yield	Kumar *et al.* 2023
10%	Wheat	Improved plant height, shoot density, dry matter accumulation, spike length and spikelets	Kaur *et al.* 2021
600 L/ha	Carrot	Enhanced nutrient availability, carotene and carbohydrate content, shoot growth and yield	Krishna *et al.* 2017
500 L/ha	Onion	Increased bulb yield, bulb weight, and girth	Pathak and Shukla 2023
50%	Garlic	Higher plant height, leaf number, bulb diameter and yield	Fazeel *et al.* 2019
75 - 100%	Okra	Increased leaf area, flowering, chlorophyll content, shoot/root biomass and pod yield	Bharadwaj *et al.* 2021
500 L/ha	Pea	Maximum pods per plant, seeds per pod, pod yield per plant and per hectare	Dhomne *et al.* 2022
500 L/ha	Pigeon pea	Increased pods per plant, seed index, dry pod weight, grain and stalk yield	Chongre *et al.* 2018
1000 L/ha	Green gram	Higher grain and stover yield	Kharat *et al.* 2021
3%	Watermelon	Increased fruit weight and number of fruits per vine	Baldaniya *et al.* 2023
3%	Broccoli	Higher protein and ascorbic acid content	Ashwini *et al.* 2022a
500 - 1000 L/ha	Marigold	Improved plant height, spread, flowering duration, flower number and yield	Ravi *et al.* 2022
500 - 1000 L/ha	Mango	Improved soil moisture, water holding capacity, fruit yield and dry matter accumulation	Sathish *et al.* 2022
500 - 1000 L/ha + 1000 kg/ha	Guava	Increased total sugars, reduced acidity, improved shelf life	Choudhary *et al.* 2022
16.08 L/plant	Pomegranate	Improved flowering, fruit set, fruit growth and yield attributes	Jhade *et al.* 2020
1.5 L/plant	Papaya	Enhanced growth, yield, early flowering, improved ascorbic acid content	Kavitha *et al.* 2022
600 kg/acre + 300 L/acre	Banana	Increased plant height, pseudostem girth, leaf area, reduced crop duration	Thankamani *et al.* 2020
10 mL/plant	Bush pepper	Enhanced root growth and root architecture	Manjunatha *et al.* 2009

7.5 t/ha	Sunflower	Increased microbial activity, nutrient solubilization and uptake	Siddappa and Devakumar 2016
1500 L/ha	Field bean (Lablab)	Increased pod number, seed number, pod and seed weight	Kadam and Kamble 2020
2000 L/ha	Turmeric	Increased tillers, leaves per tiller and dry rhizome yield	TNAU n.d.

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Authors' contributions

KC participated in drafting and writing of manuscript. VK, MS,AK participated in data collection. AMN and AY participated in proofreading of manuscript. All the authors read and agreed for the final shape of manuscript.

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Declaration of artificial intelligence (AI) tool usage:

The authors declare that AI-assisted tools were used during the preparation of this manuscript for grammar correction and generation of only one figure but prompt used were self-structured. All scientific content, data interpretation, and conclusions are solely the responsibility of the authors.

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