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A circular bioeconomy approach: transforming household kitchen waste into a soil-boosting bioformulation

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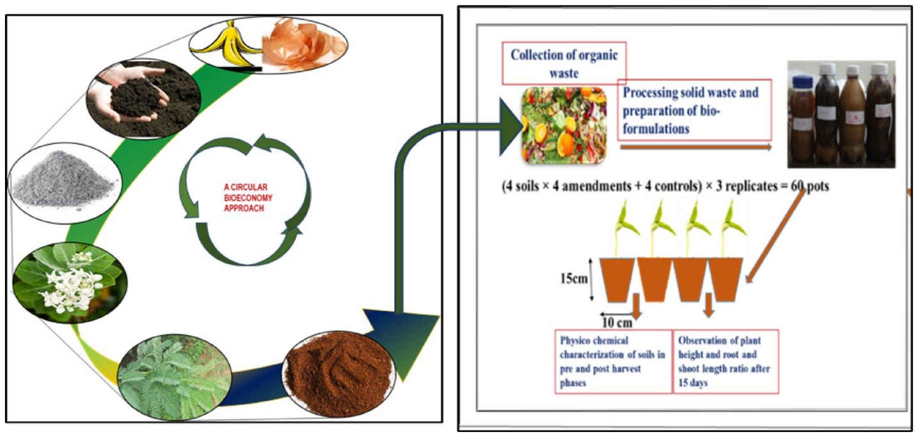
Abstract
Management of solid waste management is at the forefront of global sustainability challenges, with increasing emphasis on converting organic waste into value-added products that restore soil health and promote circular bioeconomy. This study aims to develop and evaluate bioformulations derived from fermented kitchen and agricultural waste as sustainable soil amendments for arid and semiarid regions. It investigates their short-term impact on soil fertility and plant growth, addressing key limitations like low organic carbon, high salinity, and nutrient imbalance. Four organic formulations prepared from fermented kitchen and agricultural waste were applied to different soil types of semi-arid Kachchh region. Pot experiments were conducted to assess changes in soil physico-chemical parameters and plant growth. The prepared bioenzymes significantly improved soil parameters, including reduction in pH ($F(4,5) = 5.74$, $p = 0.04$), reduced electrical conductivity, and increased organic carbon. Available P (phosphorus), K (potassium), and micronutrient levels also increased, with A4 showing the highest enhancement in Fe, Zn, and dry biomass. The results validate the promise of formulations based on organic waste as an economical and environmentally responsible substitute for synthetic inputs. This method offers useful benefits for sustainable agriculture in dry, resource-constrained regions by improving soil fertility and encouraging circular economy principles. This study is among the first to evaluate indigenous, kitchen-waste-derived bioformulations in the semi-arid soils of Kachchh, India.

Keywords Arid, Food waste, Organic fertilizers, Organic solid waste, Semiarid

Graphical abstract



1 Introduction

Improper disposal of kitchen waste in urban India presents both a pollution hazard and a missed opportunity for resource recovery. Globally, municipal solid waste generation exceeded 2.0 billion tonnes in 2020, with projections rising by 73% by 2050. Moreover, food waste alone amounted to 1.05 billion tonnes (132 kg per capita) in 2022, approximately 19% of all food produced—with households contributing 60% of this total [1, 2]. The United Nations sustainable development goals (SDG) have emphasised the role of solid waste management for a conducive future for upcoming generations [3]. Particularly SDG 12 (Responsible Consumption and Production) by promoting sustainable waste valorisation, SDG 2 (Zero Hunger) through improved crop productivity, and SDG 13 (Climate Action) by reducing greenhouse gas emissions from unmanaged kitchen waste.

Similarly, untreated solid waste is also a major environmental concern that contributes significantly to land degradation [4]. According to the 2020–21 annual report of Central Pollution Control Board of India, the total quantity of solid waste generated in the country is 160,038.9 Tonnes Per Day (TPD), of which 50,655.4 TPD (31.7% of the total waste generated), remains unaccounted or unclassified [5]. Such untreated waste can deteriorate the quality of soil and ground water by creating leachates.

Arid and semiarid soils play a critical role in global ecosystems, covering vast expanses of land and influencing the livelihoods of millions of people. These soils are characterized by low moisture content, high evaporation rates, nutrient deficiency and high alkaline pH, posing significant challenges for agriculture and ecosystem sustainability [6]. Low C and moisture content in soil is also a reason for poor soil fertility and generally leads to high emissions of greenhouse gases[7]. According to a 2014 study, 37.26% of India's land is semiarid, and 15.49% is arid [8].

Soil pollutants can have adverse effects on the soil ecosystem, leading to radical changes in soil chemistry and impacting the biochemical activities of soil flora and fauna (Huang et al. 2023; [9]). Therefore, it is important to determine proper solutions for managing these solid wastes and determining resource recovery techniques. Through continuous efforts to find solutions to this problem, many methods have been developed to treat solid waste effectively. Traditional composting practices in India, such as vermicompost and anaerobic pit composting, offer a starting point for developing localized bioformulations, though their efficacy varies widely in arid soils [10]. Scientists have identified various solutions for reutilizing organic solid wastes as effective amendments for improving soil fertility and crop growth [11]. The use of biochars from several wastes is a classic example of such recent innovation also adhering to the global practice of using Nature Based Solutions (NBS) [12]. Additionally, there are a variety of organic liquid fertilizers available on the market that have shifted farmers' attention from conventional fertilizers [13].These microbial consortia have been shown to impact soil fertility and crop growth [14]. In addition, there are other waste materials that are said to provide many plant-friendly nutrients [15]. Organic substrates such as lemon peels, jaggery, curd, wood husk, and yeast offer both fermentable sugars and diverse microbial populations that support soil health. These materials have traditionally been used in composting practices and are now gaining scientific attention for their role in ecoenzyme and biofertilizer development. Recent studies have shown that fruit and vegetable wastes, when combined with sugar-based inputs such as jaggery and inoculated with microbial agents like yeast, undergo effective fermentation to produce nutrient-rich bioenzymatic liquids suitable for agricultural use [16]. Such innovations support circular bioeconomy approaches to waste valorization and sustainable soil fertility management. Possible types of organic wastes to be utilized as an effective amendment have been elucidated in Fig. 1. Use of these organic waste to construct a novel liquid bioformulation for use as an amendment for soil and crop growth enhancement using traditional indigenous knowledge, has been the least studied topic.

Fig. 1 Representation of varieties of organic waste as a potent nutrient resource

Though in-organic waste management is researched widely with several publications on the 'waste to resource' model, there is a dearth of similar research in the domain of organic waste [17]. To address this gap, the current study focused on creating a novel liquid bioformulation from a variety of agricultural and kitchen wastes and explored its potential to increase crop growth and soil fertility. This study investigates a decentralised, circular bioeconomy approach to address these issues by creating a bioformulation from separated kitchen waste from households. This formulation uses a controlled fermentation process, in contrast to traditional composting methods, to preserve vital nutrients, support advantageous microbial communities, and enhance the physicochemical characteristics of soil. The strategy prioritises agronomic effectiveness, community-level reproducibility, and ease of production.

This study aims to evaluate the effectiveness of kitchen-waste-based liquid bioformulations in improving soil health and promoting early plant growth in semi-arid soils. We hypothesize that the bioformulations—through microbial action and organic enrichment—will improve soil physicochemical properties and positively influence initial seedling responses.

2 Materials and methods

2.1 Collection and processing of household kitchen waste

Source-segregated household kitchen waste (mainly vegetable and fruit peels and scraps) was collected from urban households. Inedible materials such as plastic, glass, and non-biodegradables were excluded manually. The biodegradable portion was chopped to 1–2 cm fragments to facilitate uniform decomposition.

2.2 Bioformulation development

The base bioformulation was prepared using the collected kitchen waste (citrus) that was chopped and was fermented in special closed containers with specific lids [18]. The microbial culture was introduced through raw materials sourced from kitchen like curd, yeast. Curd (a rich source of Lactobacillus) and baker's yeast (*Saccharomyces cerevisiae*) were added to initiate microbial fermentation. These microbial agents accelerate decomposition and nutrient mobilization. The fermentation was carried out in closed bins under mesophilic conditions (30 ± 2 °C) for 15 days with periodic mixing. Regular controlled gas release was carried out. Post-fermentation, the concoction/ecoenzyme was sieved and the liquid so obtained was stored in airtight containers at ambient temperature for subsequent analysis and field application.

2.3 Preparation of infused ecoenzymes

The above obtained base citrus ecoenzyme was used as the base for infusion with following locally sourced materials as mentioned below:

(a) A1: PCF- Base citrus formulation + 1 g of gram flour + 1 g of soil + decomposed buttermilk + 5 g of dried Prosopis juliflora leaf powder and 5 g of dried Calotropis procera leaf and stem powder.

(b) A2: CWF- Base citrus formulation + 1 g of gram flour + 1 g of soil + decomposed buttermilk + 5 g of decomposed cow dung manure and 5 g of wood ash.

(c) A3: BOCF- Base citrus formulation + 1 g of gram flour + 1 g of soil + decomposed buttermilk + 5 g of dried and powdered banana peels + 5 g of dried and powdered onion peels + 5 g of waste coffee grounds.
(d) A4: BOCFS- Base citrus formulation + 1 g of gram flour + 1 g of soil + decomposed buttermilk + 5 g of dried and powdered banana peels + 5 g of dried and powdered onion peels + 5 g of waste coffee grounds. The mixture was kept for 3 days and then filtered. This formulation was then absorbed with the required quantity of wood husk powder.

A4 included all components of A3, with the addition of wood husk, which contributed lignocellulosic material aimed at improving microbial colonization and buffering pH.

2.4 Experimental design for soil collection

In order to evaluate how the produced ecoenzyme affected soil fertility, topsoil samples (0–20 cm) [19] were collected from different farms located in the Kachchh region. The soils belonged to great group typic camborthids [20]. The samples represent various farming methods as follows. The design followed a randomized block design (RBD) with four replications. The treatments were:

S-1: Untreated and uncultivated agricultural soils.

S-2: Soils used in agriculture while using organic agricultural methods.

S-3: Soils used in agriculture that are farmed using traditional (chemical) methods.

S-4: Reddish agricultural soils used for single-crop farming techniques.

The average temperature variation in the area is 28.1 °C, with lowest temperatures of 23.8 °C and high temperatures of 38 °C. The average rainfall is about 34 cm spread across days.

The experiment was performed using all four soils in parallel pot trials. At each site, three subsamples were collected and homogenized to form one composite soil sample per soil type.

Fig. 2 Pot experiment image of crop growth after 15 days

2.5 Pot experimental design

Soils were homogenized through a 2 mm sieve and transferred to 15 inches pots. Each pot measured 15 inches in height and 10 inches in diameter and was filled with 6.5 kg of air-dried, sieved soil." Six mung bean (*Vigna radiata* L.) seeds were sown at a 2.5 cm depth in each pot. All the above prepared organic formulations were added to each type of sampled soil. Tap water was used for irrigation. Soils 1 and 4 were irrigated every 2 days, and soils 2 and 3 were irrigated every 4 to 5 days. The pots were kept in a greenhouse for 15 days. Crops were harvested after 15 days, and soils in the postharvest phase were examined for physico-chemical characterization. This experiment included three replicates. A 15-day growth period was selected to capture responses during early seedling establishment, a critical stage where nutrient availability and microbial interactions strongly influence plant development [21] Fig. 2 shows the crop growth after 15 days of amendment application with respect to control. The experiment involved 4 treatments (A1–A4) × 4 soil types × 3 replicates, resulting in a total of 48 pots arranged in a completely randomized design (CRD).

2.6 Determination of soil physico-chemical properties

Soils from the pots were homogenized through a 2 mm sieve and evaluated for physico-chemical characterization. Major nutrients were also quantified using standard methods in the pre- amendment phase. The prepared organic formulations were applied to the soils, which were subsequently sown with mung bean seeds. Soil samples from the pots were analysed for the same parameters at 15 DAS (Days After Sowing). The salinity, EC, and pH were measured using an OAKTON multiparameter PCSTestrTM 35. Soil EC and pH were measured once at the end of the experiment, following treatment exposure Soil organic carbon was measured both before and after harvest using the Walkley and Black Rapid Titration Method [22]. Available phosphorous was analysed through Olsen's method according to Olsen [23], and potassium was analysed through a flame photometer. Minor nutrients were analysed through an atomic absorption spectrophotometer (AAS) [24]. Soil texture class was identified using USDA soil texture triangle [25]. The analysis focused on short-term effects observable during early seedling development (15 DAS), including key physicochemical parameters and primary growth responses. Detailed biochemical assays will be included in future long-term trials.

2.7 Cost budget analysis of amendments prepared.

The currency exchange rates used for our bioformulation's cost–benefit analysis were fixed at 1USD = INR83.47. The prices per kilogram of gram flour (B) and jaggery (A) were determined using the State cooperative market. For this pilot study, the solid wastes (banana peels, citrus peels, coffee grounds, cow dung manure, prosopis and aak plant stem and leaves, onion peels) were collected at no cost from households and food-serving institutions. However, the labour cost for their transportation and segregation, as required by the Mahatma Gandhi National Rural Employment Guarantee Act 2005 (MGNREGA), is INR 256 per day (C). The entire amount (T) required to prepare one litre of bioformulation from 1 L water, 100gm jaggery and 1gm gram flour is calculated using Eq. 1 [17]

$$T = A + B + C \tag{1}$$

2.8 Statistical analysis

A one-way analysis of variance (ANOVA) was conducted to compare the effect of different amendments (A1, A2, A3, A4) and a control (C) on various parameters studied. probability level of 0.05 was considered to be statistically significant. The following statistical software were used to carry out various analytical procedures: SPSS version 20 (IBM), SAS version 9.3, Microsoft Excel version.

ANOVA outputs included F-values, *p*-values, and standard errors, as reflected in Tables 2 and 3. Data were tested for normality using Shapiro–Wilk and homogeneity using Levene's test.

3 Results and discussion

This study assessed how four different organic amendments derived from kitchen waste (A1 to A4) affected early-stage mung bean (*Vigna radiata* L.) growth and a variety of soil physicochemical characteristics in four different desert soil types from the Kachchh region. The pH, electrical conductivity, organic carbon, macro and micronutrient levels, and dry biomass of the soil all showed notable changes within 15 days of the amendment's application. The following interpretation of the results takes into account environmental factors, microbiological processes, and functional substrates. Although the experiment was conducted on four distinct soil, the treatment responses followed a similar trend across all soils. Therefore, the results presented here represent averaged values across soil types to highlight the general efficacy of each formulation." Table 1 depicts the physicochemical characterization of the control soils. Table 2 shows the overall statistical analysis of the physicochemical characterization in pre and post amendment phases.

3.1 Soil pH and EC: indicators of salinity and nutrient availability in soil

Despite being minor, the variations in soil pH were regular and statistically significant ($F = 5.74$, $p = 0.04$). Due to the presence of alkaline bioactive chemicals in wood husk (in A4) and ash content (in A2), amendments A2 and A4 caused a modest elevation in pH. The slight increase in pH under A4 can be attributed to the presence of alkaline

Table 1 Physicochemical characterization of pretreated experimental soils

Sr. no	Soil type	Texture class	pH (1:2)	EC (dS/m)	OC %	Avail. P(Kg/Ha)	Avail. K (Kg/Ha)	Zn (ppm)	Fe (ppm)	Mn (ppm)	Cu (ppm)
1	Agriculture soils with no treatment and no cultivation(S1)	Sandy loam	8.34	0.32	0.8	19.76	190.19	0.15	4.78	18.2	1.56
2	Agriculture soils with organic farming practices(S2)	Sandy loam	8.35	0.32	1.19	22.23	190.19	0.6	3.8	4.6	1
3	Agriculture soils with conventional (chemical) farming practices (S3)	Sandy loam	8.54	0.36	1.18	22.23	143.26	0.18	4.6	11	1.42
4	Agriculture soil (red colour) with single-crop cultivation practices (S4)	Sandy loam	7.97	1.45	1.38	19.76	153.14	0.51	6	12	1.3

Table 2 Overall descriptive analysis of the physicochemical characteristics in pre and post amendment phases

Sr. No	Parameter name	Control			Amendment 1			Amendment 2			Amendment 3			Amendment 4		
		Mean	Std. deviation	Std. error	Mean	Std. deviation	Std. error	Mean	Std. deviation	Std. error	Mean	Std. deviation	Std. error	Mean	Std. deviation	Std. error
1	pH (1:2)	8.30	0.24	0.12	8.30	0.14	0.07	8.37	0.24	0.12	8.34	0.13	0.06	8.40	0.12	0.06
2	EC (dS/m)	0.61	0.56	0.28	0.35	0.05	0.02	0.44	0.15	0.07	0.30	0.09	0.05	0.48	0.07	0.03
3	%OC	1.14	0.24	0.12	1.00	0.21	0.11	1.05	0.24	0.12	1.12	0.25	0.13	1.20	0.19	0.09
5	Avail. P (Kg/Ha)	21.00	1.43	0.71	24.70	2.02	1.01	25.32	2.36	1.18	24.08	4.22	2.11	22.23	3.49	1.75
6	Avail. K (Kg/Ha)	169.20	24.58	12.29	240.83	148.60	74.30	163.02	51.77	25.89	161.17	54.91	27.46	215.51	73.48	36.74
7	Sulphur (ppm)	3.88	2.15	1.07	4.20	1.36	0.68	3.25	0.30	0.15	7.43	9.18	4.59	4.70	1.83	0.91
8	Zn (ppm)	0.36	0.23	0.11	0.50	0.31	0.15	0.46	0.33	0.17	0.98	0.94	0.47	1.00	1.08	0.54
9	Fe (ppm)	4.80	0.91	0.45	6.75	5.37	2.69	7.28	2.97	1.48	6.85	4.20	2.10	9.50	4.54	2.27
10	Mn (ppm)	11.45	5.57	2.78	5.40	1.86	0.93	5.25	3.87	1.93	6.75	2.82	1.41	8.95	4.95	2.48
11	Cu (ppm)	1.32	0.24	0.12	0.76	0.47	0.23	1.28	0.42	0.21	1.17	0.96	0.48	1.21	0.83	0.42
12	Dry biomass	85.16	1.86	0.93	84.06	2.40	1.20	85.52	2.06	1.03	85.88	1.51	0.75	86.65	1.89	0.95

substances such as wood husk, known to buffer soil acidity through their ash content and lignocellulosic residues. On the other hand, A1 and A3 maintained pH in the neutral-to-alkaline range, which is advantageous in dry areas where high alkalinity frequently restricts nutrient uptake [7].

In comparison to the control (0.61 dS/m), a significant decrease in EC was observed in all amendments, particularly A3 (0.30 dS/m) and A1 (0.35 dS/m), suggesting a drop in soluble salt concentrations. In fermentations based on citrus peels, microbial metabolism immobilises ionic chemicals into organic complexes, reducing them [11, 26]. Because of this, these bioformulations are appropriate for deteriorated and salinity-prone soils.

3.2 Organic carbon enrichment: fuel for the health of soil

The amount of organic carbon increased with each modification. Following A3 (1.12%) and A2 (1.05%), A4 had the highest SOC (1.20%). These findings point to effective microbial humification and breakdown of waste organics. The cellulose-lignin matrix of wood husk, which contributes to the carbon pool and provides stable organic matter for microbial colonisation, is probably what causes A4's enrichment [27]. This supports claims that varied bio-substrates enhance soil aggregation and fertility over the long run [7].

3.3 Potassium and phosphorus availability: changes in the nutrient balance.

All amendments showed a significant increase in available phosphorus ($F = 25{,}373.29$; $p < 0.001$), with A2 having the highest value (25.32 kg/ha). The microbial effect on wood ash and cow dung, which are known to contain bacteria that solubilise phosphate, is responsible for this improvement [28]. In A3, banana peel also helped mobilise phosphorus by releasing organic acid, which is in line with Raha 's findings [29].

Due to potassium-rich inputs such as *Prosopis juliflora* and *Calotropis procera*, available potassium increased most in A1 (240.83 kg/ha) [15]. Because wood husk's porous structure functions as a slow-release matrix for nutrients, A4 also demonstrated good potassium retention.

3.4 Micronutrient dynamics

Improving the Availability of Trace Elements, all treatments saw a rise in iron and zinc levels, although A4 had the highest levels of both at 9.50 ppm Fe and 1.00 ppm Zn. Chlorophyll production and enzyme activation depend on these trace elements. Low molecular weight organic acids produced during fermentation are responsible for the improvements, since they chelate and solubilise these metals, hence increasing their bioavailability [30].

Trends in manganese and copper were more erratic. Although their total levels decreased after treatment, this could be because they were absorbed by microbial biomass that was growing or changed into less mobile forms [31]. These findings call for more research on the interactions between microbes and metals in short-term degrading substrates.

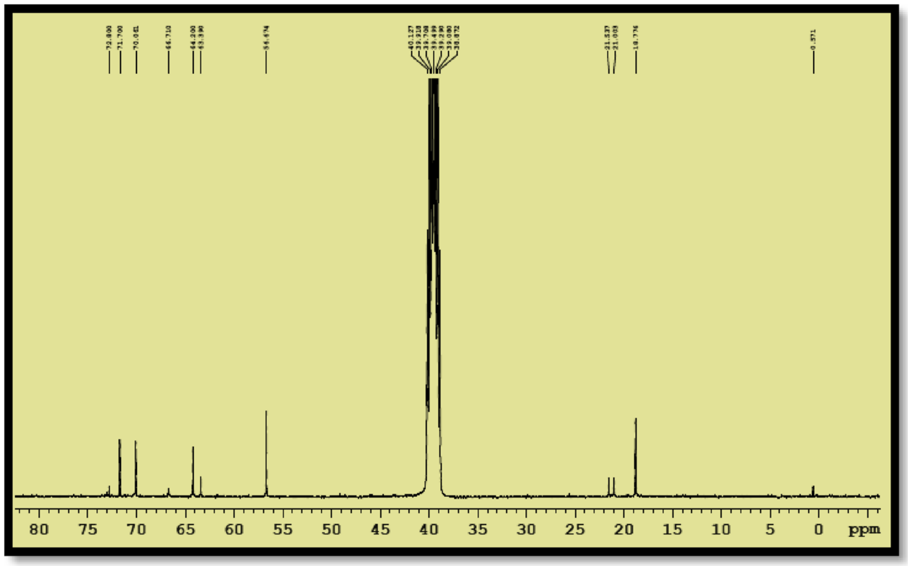


Fig. 3 IR spectrum of the base bioformulation

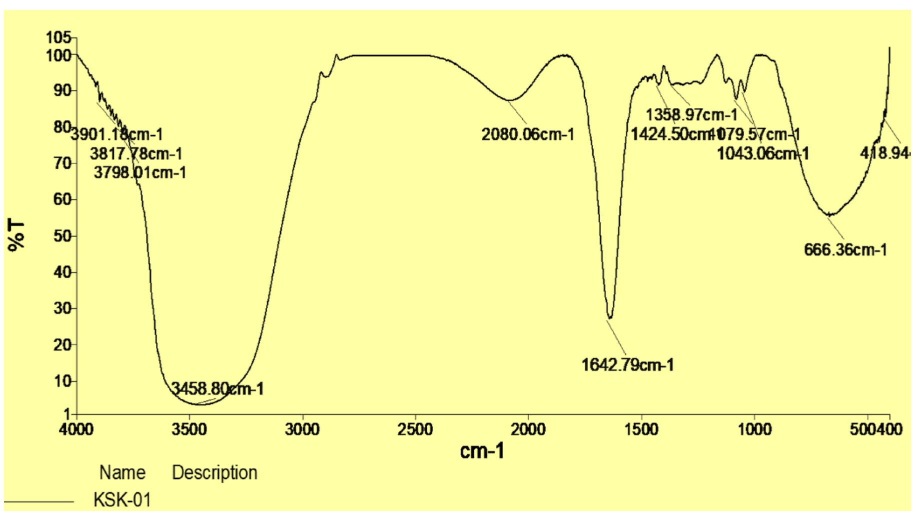


Fig. 4 NMR spectra of the sample formulation

3.5 Dry biomass response: accelerated growth

All treatments showed a slight improvement in dry biomass as compared to the control (F = 7601.35, $p < 0.001$), with A4 exhibiting the greatest performance (86.65 g). A combinatorial enhancement in microbial colonisation, organic matter, and nutrient delivery is responsible for this early-stage vigour (Patidar et al. 2023). Significantly, soil history was a factor: soils with a history of organic management (S2) were more responsive than those with a history of chemical treatment (S3), indicating a legacy effect in the compatibility of microbial communities.Among the formulations, A4 showed the highest improvement in soil pH, EC stabilization, and nutrient availability, while A3 was most effective in enhancing potassium and organic carbon levels. A2 favored nitrate enrichment.

3.6 Chemical examination of the bio formulation:

To assess the chemical characteristics of the citrus-based bioformulation, infrared (IR) and nuclear magnetic resonance (NMR) spectroscopy were used (Figs. 3 and 4). The results confirmed citric acid generation, demonstrating that microbial activity converts sugar substrates during fermentation. IR spectra were collected with a Perkin Elmer Spectrum Two FT-IR spectrometer. The IR spectrum identified essential functional groups, including a broad band at 3000–3500 cm^{-1} for O–H stretching in carboxylic acids, a sharp band at 1740 cm^{-1} for C=O stretching in carbonyl groups, and bands at 1400–1600 cm^{-1} for C–H bending. Additional bands at 1358 cm^{-1} and 1000–1100 cm^{-1} correspond to C–O stretching and C–O–H bending vibrations, respectively.

C-13 NMR spectroscopy was performed in DMSO using an Advance Neo Nano Bay 400 MHz to analyze the carbon environment of the bioformulation. Signals in the 170–180 ppm range indicated carbonyl carbons in carboxylic acids, while signals at 60–80 ppm suggested carbons adjacent to hydroxyl groups. Carbons in the alkyl chain resonated in the 10–50 ppm range, providing a detailed molecular structure. Figure 4 shows the NMR spectra.

3.7 Cost budget analysis: pocket friendly approach

The bioformulations' economic viability was assessed through an initial cost study. The materials utilised, like gramme flour, jaggery, and organic waste from the home, are affordable and readily available locally. Including material and labour, the cost to prepare 1 L of bioformulation was about ₹262.07 based on current market rates and labour pay (INR 256/day under MGNREGA).

The projected cost of scaling this up to treat 100 kg of organic waste (with 15 g infused per litre) was ₹40,743. The total material cost is still low because the organic wastes (banana peels, citrus peels, onion peels, coffee grounds, etc.) were freely obtained from homes and food establishments. The entire amount (T) required to prepare one litre of bioformulation from 1 L water, 100gm jaggery and 1gm gram flour is calculated using Eq. 1 (Fig. 5),

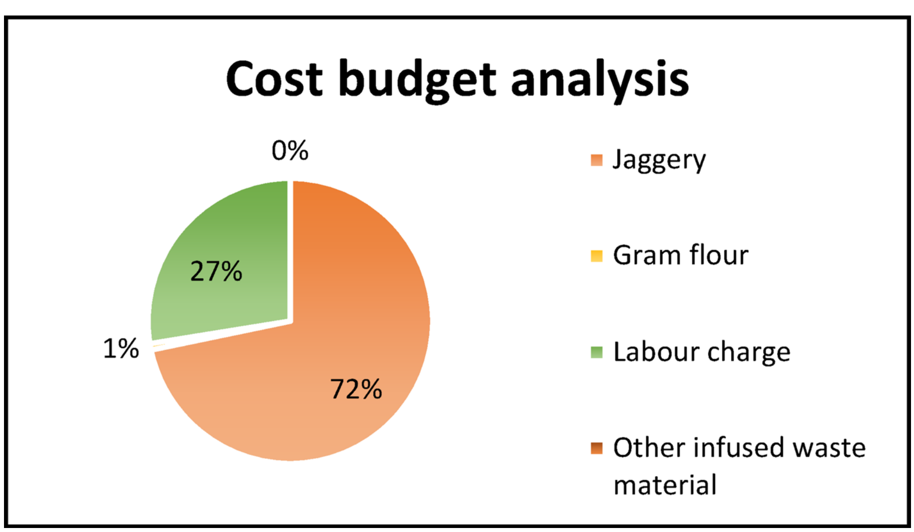


Fig. 5 Percentage distribution of raw material cost for Bioformulation preparation

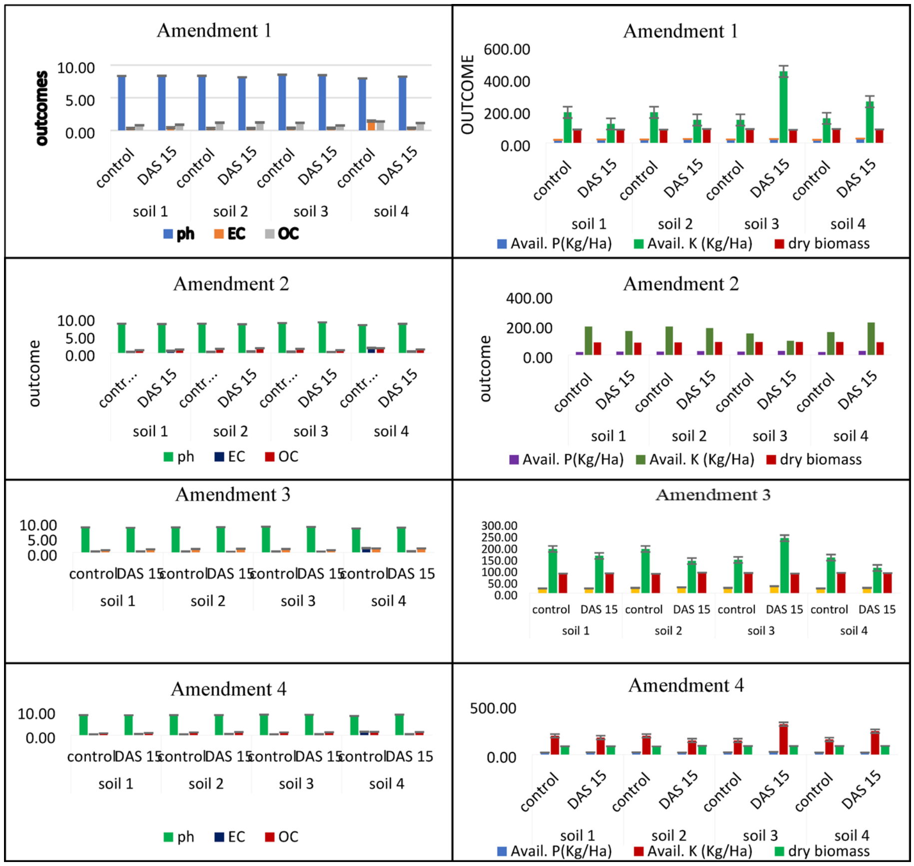


Fig. 6 Graphical Illustration depicting effect of different amendments on experimental soils

$$\begin{aligned} T &= A + B + C \\ &= 6 + 0.07 + 256 \\ &= 262.07\text{INR} \end{aligned} \tag{2}$$

When compared to commercial organic or synthetic soil amendments, this cost-effective manufacturing strategy implies that the synthesis of these formulations at the community level or in a decentralised manner is economically feasible. Furthermore, it gives rural people access to livelihood prospects through programs like MGNREGA, coordinating the intervention with the objectives of employment creation and sustainable development.

3.8 Scientific validation and statistical understanding

All measured parameters, including pH, EC, OC, available P and K, and all micronutrients, showed significant variation across treatments, according to the one-way ANOVA, indicating that the variations were caused by the bioformulations rather than being random (Fig. 6). The observed results' rigour and reproducibility are confirmed by the complete F-statistics (Table 3).

4 Conclusion

This study emphasises the potential of fermented bioformulations made from organic waste that is readily available as inexpensive, environmentally beneficial soil additions. The most consistent increases in soil fertility and plant biomass were observed

Table 3 Combined F statistics of the impacts of all the amendments for the various parameters

Parameter	Source of variation	SS	df	MS	F	*P*-value	F crit
pH	Between groups	0.01	4	0.00	5.74	0.04	5.19
	Within groups	0.0024	5	0.0005			
	Total	0.013332	9				
EC	Between groups	0.093399	4	0.02335	29.23823	0.001156	5.192168
	Within groups	0.003993	5	0.000799			
	Total	0.097392	9				
OC	Between groups	0.061111	4	0.015278	76.27484	0.000114	5.192168
	Within groups	0.001002	5	0.0002			
	Total	0.062113	9				
P	Between groups	25.83001	4	6.457503	25373.29	0.00	5.192168
	Within groups	0.001273	5	0.000255			
	Total	25.83129	9				
K	Between groups	10449.84	4	2612.461	4406986	0.00	5.192168
	Within groups	0.002964	5	0.000593			
	Total	10449.85	9				
Zn	Between groups	0.738824	4	0.184706	1940.189	0.0000	5.192168
	Within groups	0.000476	5	9.52E-05			
	Total	0.7393	9				
Fe	Between groups	22.58059	4	5.645148	29083.71	0.0000	5.192168
	Within groups	0.00097	5	0.000194			
	Total	22.58156	9				
Mn	Between groups	55.25046	4	13.81262	18136.31	0.0000	5.192168
	Within groups	0.003808	5	0.000762			
	Total	55.25427	9				
Cu	Between groups	0.397447	4	0.099362	1528.644	0.0000	5.192168
	Within groups	0.000325	5	6.5E-05			
	Total	0.397772	9				
Dry biomass	Between groups	7.476687	4	1.869172	7601.35	0.0000	5.192168
	Within groups	0.00123	5	0.000246			
	Total	7.477917	9				

in treatment A4 (BOCFS). The strategy encourages sustainable agriculture in dry areas, lessens dependency on synthetic fertilisers, and advances circular economy principles. These findings present a viable, scalable substitute for waste valorisation and early-stage soil health improvement. While short-term benefits were evident, future studies should evaluate the long-term sustainability of these formulations, especially in terms of microbial community shifts and nutrient cycling under field conditions. Promoting localized preparation of such bioformulations not only valorizes waste but also opens avenues for community-level entrepreneurship, especially for self-help groups and rural cooperatives. This aligns well with the principles of circular bioeconomy, by turning waste into inputs and strengthening environmental and economic resilience.

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Author contributions
The study was led by Dr Seema B. Sharma under whose guidance Miss Khayali Vaidya carried out her doctoral work and this is a part of the doctoral work at Ecological Sustainability, Soil & Microbial Innovation Lab (ESSMI Lab)Department of Environmental & Life Sciences, KSKV Kachchh University, Bhuj, Gujarat, India. Khayali Vaidya: conceptualization, Methodology, Formal analysis, Investigation, writing—Original Draft Seema B Sharma: Conceptualization, Methodology, Formal analysis, Resources, writing—Original Draft, Supervision Jagruti sanghvi: Writing—Original Draft, Abhiroop Chowdhry: Writing—Original Draft, Supervision, Manish Solanki: Formal analysis, Investigation.

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Data is provided within the manuscript.

Declarations

Ethics approval and consent to participate
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Consent to publication
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Competing interests
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