

SEED-WASTE POWDER AS A SOIL AMENDMENT FOR ENHANCING MICRONUTRIENT BIOAVAILABILITY AND NUTRITIONAL QUALITY OF FOOD CROPS

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ABSTRACT

Declining soil fertility and micronutrient deficiencies are important constraints to crop productivity and nutritional quality. This study evaluated seed-waste powder as a soil amendment for improving the growth, yield-related characteristics, and nutritional quality of wheat (*Triticum aestivum*). The amendment was incorporated into agricultural soil at 2% (T1), 5% (T2), and 10% (T3), while untreated soil served as the control (T0). Wheat growth parameters, including plant height, leaf number, fresh biomass, dry biomass, and leaf area, were evaluated along with iron (Fe), zinc (Zn), protein, and fiber contents. Progressive improvement in wheat growth was observed with increasing amendment concentration. Plant height increased from 22.5 cm in the control to 25.3, 28.7, and 31.5 cm at 2%, 5%, and 10% amendment, respectively. Similarly, leaf number increased from 8 to 14, while fresh biomass increased from 45 to 80 g and dry biomass from 7.5 to 14.3 g. Leaf area increased from 120 to 195 cm². Nutritional parameters also improved, with Fe increasing from 2.5 to 4.6 mg/100 g and Zn from 1.4 to 2.9 mg/100 g. Protein and fiber contents increased from 2.8% and 0.8% in the control to 4.5% and 1.6%, respectively, at 10% amendment. Overall, seed-waste powder demonstrated potential as a sustainable soil amendment for enhancing wheat growth and nutritional quality, with the 10% treatment producing the greatest improvement among the tested concentrations.

KEYWORDS: Seed-waste powder; soil amendment; micronutrient bioavailability; nutritional quality; soil fertility; sustainable agriculture.

1. INTRODUCTION

Micronutrient deficiency in agricultural soils is an important constraint to crop productivity, soil fertility, and the nutritional quality of food. Essential micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B) are required in relatively small quantities but are fundamental to plant growth, enzyme activation, photosynthesis, metabolism, and reproductive development. In India, deficiencies of phyto-available Zn, Fe, Mn, Cu, and B have been widely reported across agricultural soils, with important implications for crop productivity and nutritional quality (Shukla et al., 2021). The availability of these nutrients is influenced by soil properties such as pH, organic matter, moisture, and interactions with other nutrients. Continuous cropping, imbalanced fertilizer application, and depletion of soil organic matter can further alter micronutrient availability and nutrient-use efficiency (Saha et al., 2019). Conventional mineral fertilizers provide readily available nutrients; however, their indiscriminate or excessive use may contribute to nutrient imbalance and deterioration of soil quality. Therefore, sustainable approaches that improve nutrient cycling while maintaining soil health are increasingly important. Organic amendments can influence soil physical, chemical, and biological properties and can enhance nutrient cycling and plant nutrient availability (Mohanty et al., 2013; Celestina et al., 2019). In particular, the incorporation of organic matter can modify micronutrient transformations and increase the water-soluble and exchangeable fractions of several micronutrients, thereby influencing their availability to plants.

Food-processing and agricultural wastes represent an underutilized source of organic matter and nutrients. Fruit and seed wastes contain minerals, dietary fibre, phytochemicals, and other bioactive compounds and can therefore be valorized rather than treated solely as waste (Zahid & Khedkar, 2022). Recent research has highlighted the conversion of food waste into soil amendments as a promising strategy for nutrient recovery, soil improvement, and sustainable crop production (Du et al., 2023). Similarly, the valorization of non-edible fruit seeds is increasingly recognized as an important component of the circular bio economy and sustainable resource utilization (Sharma et al., 2024). The present study therefore investigates seed waste powder as a sustainable soil amendment for improving micronutrient availability and supporting crop growth and nutritional quality. The study evaluates the physicochemical and mineral characteristics of selected seed waste powders and examines their effects on soil properties, micronutrient availability, plant growth, and nutrient uptake. The novelty of the research lies in integrating agricultural waste valorization, soil nutrient management, and crop Biofortification into a single framework, thereby exploring a potentially low-cost and environmentally sustainable pathway for

nutrient recycling, improved soil health, and enhanced nutritional quality of food crops.

2. MATERIALS AND METHODS

2.1 Collection and Preparation of Seed Waste Powder

Four types of fruit and plant seed wastes, namely mango (*Mangifera indica*), jamun (*Syzygium cumini*), date (*Phoenix dactylifera*) and neem (*Azadirachta indica*) were selected for the study based on their availability and potential mineral and organic matter content. The seed wastes were collected from local fruit-processing and household sources and transported to the laboratory in clean, sealed containers. Foreign materials and adhering pulp were removed manually, followed by thorough washing with distilled water. The cleaned seeds were dried at 50–60°C until a constant weight was obtained. The dried seeds were ground using a laboratory grinder and passed through a 60-mesh sieve to obtain a uniform seed waste powder. The prepared powders were stored in airtight polyethylene containers until further analysis and experimental application.

Fig. 1 Various types of Seed Waste

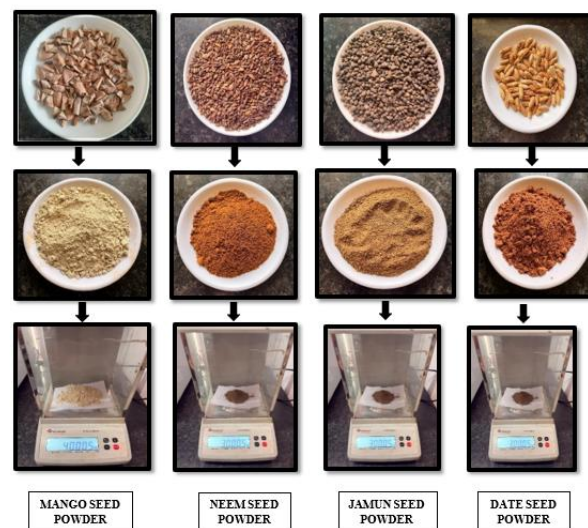


Fig. 2 Collected Seed Waste Powder

2.2 Soil Collection and Characterization

Representative soil samples were collected from selected agricultural fields at a depth of approximately 0–15 cm using clean sampling tools. The samples were thoroughly mixed to obtain composite samples, air-dried, gently crushed, and passed through a 2-mm sieve before analysis. Baseline soil characteristics, including pH, organic matter and available micronutrients, were determined using standard soil analytical procedures. The initial concentrations of **Fe, Zn, Mn, Cu, and B** were recorded to establish the baseline nutrient status of the experimental soil.

Fig. 3 Collection of Soil sample



2.3 Preparation of Seed Waste Treatments

The seed waste powders were incorporated into the soil at different application levels to evaluate their effects on soil nutrient availability and crop growth. The experimental treatments consisted of a control (T0; 0% seed waste powder), T1 (2%), T2 (5%), and T3 (10%) seed waste powder. Where required, the seed waste powders were used individually or as a standardized composite mixture prepared from the selected seed wastes. The required quantity of powder was thoroughly mixed with the experimental soil to ensure uniform distribution.

Table 1: Different ratios of mixed seed waste powder

Treatment Code	Seed Waste Powder (%)	Seed Type Ratio
T0 (Control)	0%	Not Applicable
T1	2%	1:1:1:1
T2	5%	1:1:1:1
T3	10%	1:1:1:1

2.4 Soil Sampling and Treatment

Bulk soil samples were collected from the top 0–15 cm soil layer of an agricultural field located in District Lucknow, Uttar Pradesh. The site is characterized by a loamy texture and moderate fertility. The soil was air-dried, crushed, and sieved through a 2 mm mesh to remove debris and standardize the texture.

Table 2: Physicochemical Properties of Soil from 4 Untreated Areas

Sample Code	pH	EC (dS/m)	Organic Carbon (%)	Bulk Density (g/cm ³)	Water Holding Capacity (%)	CEC (meq/100g)
S1	6.3	0.22	0.68	1.48	37	10.5
S2	6.5	0.25	0.74	1.45	38	11.0
S3	6.6	0.27	0.72	1.43	39	11.2
S4	6.4	0.24	0.70	1.46	36	10.8

The experiment was conducted in pots under controlled conditions using four soil samples, each subjected to one of the following treatments- Here's a table based on the given treatments, showing the different ratios of mixed seed waste powder (jamun, date, neem, mango in equal proportions) applied to soil:

Table 3. Experimental Treatments and Seed Waste Powder Application

Treatment Code	Seed Waste Powder (%)	Jamun	Date	Neem	Mango	Seed Waste Ratio (J:D:N:M)
T0 (Control)	0%	0%	0%	0%	0%	Not Applicable
T1	2%	0.5%	0.5%	0.5%	0.5%	1:1:1:1
T2	5%	1.25%	1.25%	1.25%	1.25%	1:1:1:1
T3	10%	2.5%	2.5%	2.5%	2.5%	1:1:1:1

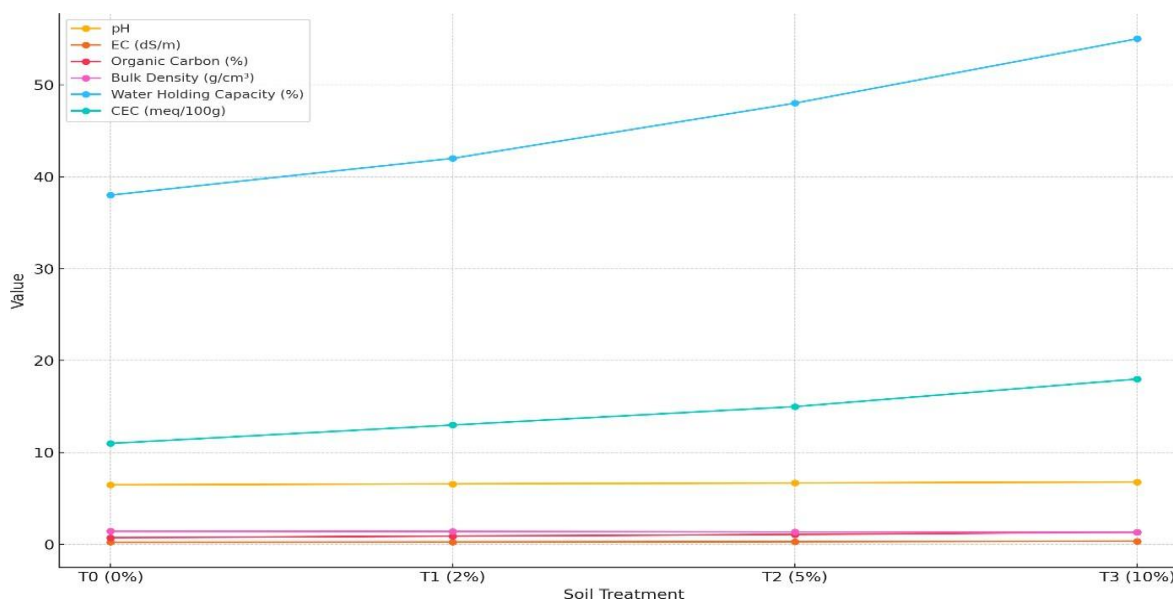


Fig. 4 Physicochemical Properties of Soil under Different treatments

Here's the graph showing changes in soil physicochemical properties under different treatments (T0–T3) with increasing seed waste powder percentages. Let me know if you'd like separate graphs for each property or want to include micronutrient data (Fe, Zn, etc.) too.

2.5 Crop Experiment

A pot experiment was conducted under controlled conditions to evaluate the effect of seed waste-based soil amendment on crop growth and nutrient uptake. Wheat (*Triticum aestivum* L.) was selected as the test crop. Uniform seeds were surface-cleaned and sown in pots containing a predetermined quantity of experimental soil. The respective seed waste treatments were incorporated into the soil before sowing, while the control received no seed waste amendment. All treatments were maintained under similar environmental conditions with uniform irrigation throughout the experimental period. Each treatment was maintained with appropriate biological replicates.

Table 4: Treatment combinations for the development of seed waste powder

Treatment	Plant Height (cm)	Leaf Number	Fresh Biomass (g)	Dry Biomass (g)	Leaf Area (cm²)	Iron (Fe) (mg/100g)	Zinc (Zn) (mg/100g)	Protein (%)	Fiber (%)
T0 (Control)	22.5	8	45	7.5	120	2.5	1.4	2.8	0.8
T1 (2%)	25.3	10	55	9.2	145	3.1	1.8	3.3	1.1
T2 (5%)	28.7	12	68	11.8	170	3.8	2.3	3.9	1.3
T3 (10%)	31.5	14	80	14.3	195	4.6	2.9	4.5	1.6

2.6 Assessment of Plant Growth Parameters

Plant growth was monitored throughout the experimental period. At harvest, growth parameters including plant height (cm), number of leaves, fresh biomass (g), dry biomass (g), and leaf area (cm²) were recorded. Plant height was measured from the soil surface to the tip of the highest leaf. Fresh biomass was recorded immediately after harvesting, while dry biomass was determined after drying the plant material to constant weight. Leaf area was measured using a suitable leaf-area measurement method.

2.7 Determination of Soil and Plant Micronutrients

Following crop harvest, soil samples were collected from each treatment and analyzed for available Fe, Zn, Mn, Cu, and B to determine changes in micronutrient availability resulting from seed waste application. Plant samples were washed, oven-dried, ground, and subjected to acid digestion. The concentrations of Fe, Zn, Mn, and Cu were determined using AAS, while boron was estimated using a suitable spectrophotometric procedure. Nutrient uptake was calculated based on the nutrient concentration and corresponding plant dry biomass.

2.8 Statistical Analysis

All experimental measurements were performed in replicates, and the results were expressed as mean ± standard

deviation (SD). The data were statistically analyzed using SPSS software. One-way analysis of variance (ANOVA) was performed to determine significant differences among treatments, followed by an appropriate post-hoc test where applicable. Differences were considered statistically significant at $p < 0.05$. Where required, the relationship between seed waste treatment, soil micronutrient availability and plant growth parameters was evaluated using correlation analysis.

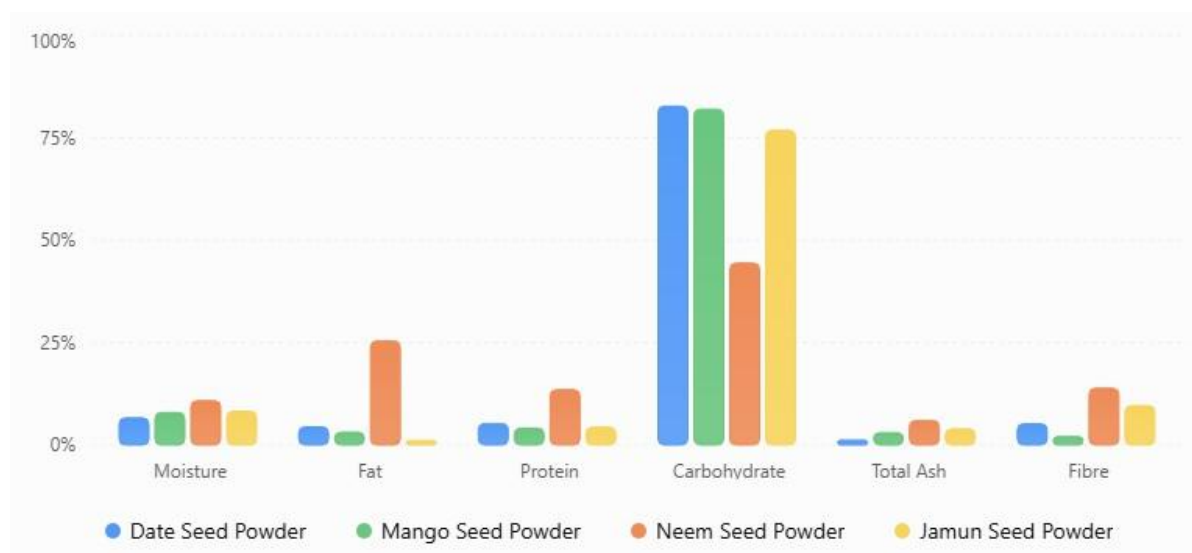
3. RESULTS AND DISCUSSION

3.1 Physicochemical Characteristics of Seed Waste Powders

The physicochemical analysis demonstrated considerable variation among the selected seed waste powders, namely mango, jamun, date, and neem seeds. Differences in moisture, ash, protein, fat, fibre, carbohydrate, and pH indicated that the seed wastes possessed distinct chemical characteristics. The relatively high organic matter and mineral content observed in the seed wastes support their potential use as organic soil amendments. Plant-derived residues can contribute organic carbon and nutrients to soil and may influence microbial activity, nutrient cycling, and soil fertility (Saha et al., 2019; Celestina et al., 2019).

Table 4: Nutritional Composition of Different Seed Powder

S. No	Parameter	Date Seed Powder	Mango Seed Powder	Neem Seed Powder	Jamun Seed Powder
1	Moisture	6.57	7.89	10.77	8.21
2	Fat	4.38	3.08	25.40	1.07
3	Protein	5.19	4.08	13.48	4.32
4	Carbohydrate	82.71	81.98	44.39	76.85
5	Total Ash	1.15	2.97	5.96	3.87
6	Fibre	5.14	2.00	13.82	9.55



The variation in mineral composition among the seed wastes was particularly relevant to their potential application for improving micronutrient availability. Seed materials contain minerals that may gradually become available following decomposition and mineralization. Thus, their incorporation into soil provides an opportunity to recycle nutrients that would otherwise be lost as food-processing or household waste. Such valorization is consistent with the principles of circular agriculture, in which organic residues are converted into useful agricultural inputs rather than being discarded (Du et al., 2023).

Table 5: Phytochemical Properties

Component	Value	Method Used
Total Phenolics	2.5 – 4.8 mg GAE/g	Folin-Ciocalteu method

Total Flavonoids	1.5 – 3.2 mg QE/g	Aluminium chloride colorimetric assay
Tannins	Moderate presence	Tannin precipitation method
Antioxidant Activity	High (qualitative)	DPPH radical scavenging assay

3.2 Mineral Composition of Seed Waste Powders

The selected seed wastes exhibited appreciable concentrations of essential minerals, including Fe, Zn, Mn, Cu, and B. However, the concentration varied according to seed type. Such differences may be associated with species-specific mineral accumulation, physiological characteristics, growing conditions, and the mineral composition of the parent plant.

Table 6: Mineral Content of Individual Seed Powders

Mineral	Jamun Seed	Date Seed	Neem Seed	Mango Seed
Nitrogen (N)	1,600	1,800	2,200	1,700
Phosphorus (P)	220	240	310	280
Potassium (K)	650	700	820	750
Calcium (Ca)	170	160	190	180
Magnesium (Mg)	110	105	130	115
Iron (Fe)	10	9	12	11
Zinc (Zn)	3.2	2.8	3.5	3.0
Copper (Cu)	0.7	0.8	1.0	0.9
Manganese (Mn)	2.5	2.0	3.0	2.7
Boron (B)	0.4	0.5	0.6	0.4

The presence of these micronutrients indicates that seed waste powder can serve as a potential supplementary source of plant nutrients. Following incorporation into soil, organic residues undergo decomposition and microbial transformation, which may release organically bound nutrients into potentially available forms. Organic matter can also influence micronutrient availability by affecting soil pH, complexation, adsorption–desorption processes, and microbial activity (Saha et al., 2019). Therefore, the mineral contribution of seed waste should be considered together with its effects on the overall soil environment.

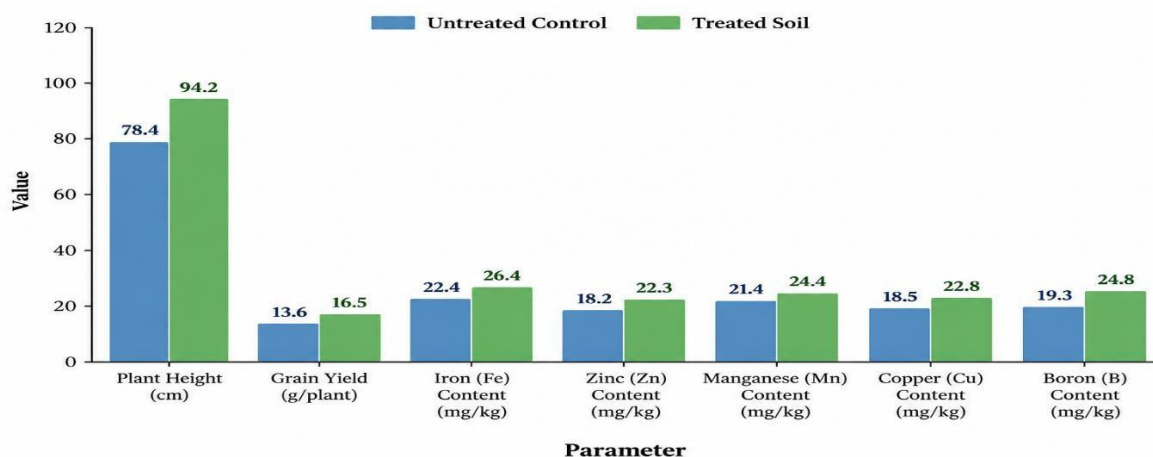
3.3 Effect of Seed Waste Application on Soil Micronutrient Availability

Application of seed waste powder resulted in treatment-dependent changes in the availability of Fe, Zn, Mn, Cu, and B in the experimental soil. The amended treatments showed a tendency toward greater micronutrient availability compared with the untreated control, particularly at the higher application levels. This response suggests that seed waste decomposition may have contributed to nutrient release and modification of soil conditions.

Table 7: Effect of Seed Waste Powder Application on Plant Growth and Micronutrient Content

Parameter	Untreated Control	Treated Soil
Plant Height (cm)	78.4	94.2
Grain Yield (g/plant)	13.6	16.5
Iron (Fe) Content (mg/kg)	22.4	26.4
Zinc (Zn) Content (mg/kg)	18.2	22.3
Manganese (Mn) Content (mg/kg)	21.4	24.4
Copper (Cu) Content (mg/kg)	18.5	22.8

Boron (B) Content (mg/kg)	19.3	24.8
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The improvement in micronutrient availability may be attributed to the combined effects of organic matter addition, microbial decomposition, and the release of mineral elements from the seed matrix. Organic amendments can modify soil chemical properties and increase the availability of nutrients through mineralization and changes in nutrient-binding processes (Mohanty et al., 2013; Saha et al., 2019). However, the response may not necessarily increase linearly with application rate because excessive organic amendment can alter soil pH and nutrient interactions. Therefore, an optimum application rate is important for achieving maximum nutrient availability without creating nutrient imbalance.

3.4 Effect on Wheat Growth Parameters

The application of seed waste powder positively influenced the growth performance of wheat compared with the untreated control. Differences were observed in plant height, number of leaves, fresh biomass, dry biomass, and leaf area among the treatments. The higher-performing treatment indicates that improved soil nutrient availability was associated with better vegetative development. Increased plant height and leaf production may reflect improved availability of essential nutrients required for cell division, chlorophyll formation, enzymatic activity, and photosynthesis. Similarly, greater fresh and dry biomass indicates improved accumulation of plant structural and metabolic materials. The response of wheat therefore suggests that seed waste-derived nutrients were not only retained in the soil but were potentially available for plant uptake.

The observed response also supports the concept that organic amendments can improve crop productivity through multiple mechanisms rather than simply supplying nutrients. Addition of organic materials can improve soil structure, water-holding capacity, microbial activity, and nutrient cycling, thereby creating a more favorable rhizosphere environment (Celestina et al., 2019).

3.5 Effect on Plant Micronutrient Uptake

The concentration and uptake of Fe, Zn, Mn, Cu, and B in wheat plants varied among the treatments. Seed waste-amended treatments generally demonstrated improved nutrient accumulation compared with the control. Increased micronutrient uptake may be attributed to greater availability of these elements in the rhizosphere following decomposition of the seed waste material.

Micronutrient uptake is determined not only by the total concentration of nutrients in soil but also by their chemical form, mobility, root-zone conditions, and interaction with other soil components. Consequently, an increase in total soil micronutrient concentration does not always result in a proportional increase in plant uptake. The present findings indicate that seed waste amendment may have promoted both nutrient release and plant accessibility, although the magnitude of response depended on the treatment.

4. CONCLUSION

Overall, the findings demonstrate the potential of seed waste powder as a low-cost and sustainable soil amendment for improving soil micronutrient availability and supporting crop growth. The beneficial response of wheat may be attributed to the combined contribution of nutrients and organic matter supplied by the seed wastes. The conversion of mango, jamun, date, and neem seed wastes into soil amendments also provides a practical strategy for reducing organic waste while recovering valuable nutrients. The study therefore establishes a link between food-waste valorization, soil nutrient management, and crop nutritional improvement. Rather than treating seed residues as waste, their controlled incorporation into agricultural soil can contribute to nutrient recycling and potentially reduce dependence on synthetic fertilizers. Nevertheless, the effectiveness of seed

waste amendments depends on their composition, application rate, decomposition characteristics, and the initial fertility status of the soil. Further long-term field studies are required to determine their effects on soil microbial activity, nutrient-use efficiency crop nutrient density, and sustainability under field conditions.

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