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Research Article

Reuse of Sewage Sludge as Organic Agricultural Products: An Efficient Technology-Based Initiative

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Rapid urbanisation has led to a dramatic increase in sewage sludge production. There are limited methods of managing sewage sludge along with high energy and monetary investment. A cost-effective, environment-friendly, and sustainable solution needs to be developed for the management of sewage sludge. In the current study, sludge from the Jagjeetpur sewage treatment plant (STP) had been collected, composted, and characterized during January and February 2022. A comparison of STP sludge compost and compost made from farmyard manure showed the presence of essential agricultural nutrients in them, due to which they find application for plant growth. Two products, Jaivik Poshak and Jaivik Prom, containing farmyard compost, were compared with the amended version of the same, containing compost from STP sludge instead of normal compost. The results showed that the modified Jaivik Poshak was the best for maintaining pH and increasing electrical conductivity. The available nitrogen in the soil upon its application increased by 1.6 times ($p < 0.001$) with respect to control, and it brought about 100% tomato seed germination within sixteen days. The above finding has been validated by goodness of fit value, factor analysis, and hierarchical analysis. The product, modified Jaivik Prom increased organic carbon content and brought about 5.81 and 8 times the enhancement in available phosphorous ($p < 0.001$) and potassium ($p < 0.001$) content in soil, respectively, with respect to the control set. The heavy metal content in the soil as a result of all types of treatment was within the permissible limit. This study thus proves that sludge from STP may be used for agricultural uses after proper fortification and testing to convert waste to wealth along with environmental sustenance.

1. Introduction

The semisolid slurry generated from various industrial processes, such as wastewater treatment and on-site sanitation systems, is known as sludge. It may be generated as a settled suspension from drinking water treatment, as sewage sludge from wastewater treatment, or as faecal sludge from septic tanks [1, 2]. After the treatment of wastewater in the treatment plant, 99% of the water is recovered and discharged as rejuvenated water. The remaining 1% which comprises solids is sludge.

The treatment of wastewater includes several stages. During preliminary treatment, which involves the removal of large particles like sticks, stones, plastic, etc., the screened material is typically landfilled and does not become a part of the sludge. Primary treatment comprises gravity, sedimentation, and floatation, during which half of the solids that enter this stage are removed and become the primary sludge, comprising both organic and inorganic constituents [3]. Secondary treatment involves microbes that have the ability to degrade organic pollutants, thereby becoming part of the sludge. Tertiary treatment is done to reduce the nitrogen and phosphorus components, suspended solids, and biological oxygen demand that add to the total sludge volume. On average, dry sludge contains 50–70% organic matter, 30–50% mineral content, 3.4–4% nitrogen, 0.5–2.5% phosphorous, and several other nutrients, depending on the type of waste treated and the stabilization processes involved [4].

The availability of modern technologies for wastewater treatment has also imparted an increase in sludge production. Owing to the rapid urbanisation and industrialization, the quantity of sludge produced has become large, and hence special attention is required for its management. Data on sludge production from 2014 to 2019 all over the world were obtained from Eurostat [5] which showed that sludge production had increased within a range of 13.57 times for Bosnia and Herzegovina to 0.65 times for Ireland in the stated period (range for countries for which data are available). Estimates suggest that Europe alone produce about 100 million tones of dry solids [6]. A range of techniques are currently accessible for the management of sludge, an important facet of which includes its utilization within the agricultural sector [7]. The application of significant quantities of untreated sludge without proper control measures can lead to the infiltration of heavy metals, phenolic compounds, and polycyclic aromatic compounds into the soil, groundwater, and adjacent water bodies, resulting in substantial alterations in soil fertility and harm to plant and animal life [8, 9]. It is important to pretreat the sludge, make it suitable to meet legal regulations, and then use it for a particular purpose [10, 11]. Nevertheless, pretreatment technologies are characterized by their complexity and high cost, hence raising concerns over the proper disposal of concentrated contaminants that are extracted from the sludge [12]. Thermal incineration represents an additional alternate method that effectively diminishes the quantity of sludge. The ash produced by the process of incineration necessitates alternative approaches for achieving cyclization [13, 14]. According to Cieślik et al. [15], the byproducts resulting from the process of incineration have potential applications in the cementing sector as well as in vitrification processes. There are alternative approaches available for the extraction of useful compounds from the sludge. The production of adsorbents can be achieved through the anaerobic pyrolysis of sewage sludge, with the incorporation of different reactants. In addition, pyrolysis oil is a by-product that can be utilised as a source of fuel, resulting in the partial recovery of sludge [15, 16]. Phosphorus recovery is an additional technology that is commonly employed by the majority of treatment plants.

Few researchers have shown the utilization of sludge for agricultural use. Brunetti et al. [17] reported a higher yield of tomatoes with the combined application of sewage sludge with inorganic fertilisers when compared to the use of inorganic fertilisers alone. The quality remained unchanged as a result of such an application and even though metals were found in tomatoes, they were not beyond the threshold limit. Aleisa et al. also showed a reduction in production of chemical fertilisers [18, 19] as well as a lesser impact on the climate by the circular economy approach if sludge could be reused in Kuwait [20].

Underdeveloped nations primarily dispose of sludge at the source, which thereby creates environmental problems and risks for humans and aquatic life [8]. The wastewater treatment processes concentrate heavy metals, organic pollutants, and pathogens. Sludge disposal can therefore bring about the release of toxic components into the environment, which can thereby enter the food chain [21–23]. Although landfilling is an economical and low-energy-consuming process, it becomes a significant source of CH_4 and N_2O which are greenhouse gases [24]. Landfilling is also incapable of utilising any of the nutrients that are present in the sludge. Landfill leachate containing P and heavy metals can also significantly affect groundwater and surface waters. Land application of sludge also has many benefits, as it improves soil quality and is inexpensive. However, land application is also limited owing to its heavy metal, micropollutant, and pathogenic microbe content [25].

On the other hand, sewage sludge contains valuable plant nutrients such as nitrogen, phosphorous, potassium, and micronutrients. The application of sludge to soil helps in the recycling of nutrients and most importantly in the organic form [26]. Thus, in this study, sludge was utilised as one of the components of organic fertilisers. The ultimate properties of the developed products were studied to understand their suitability for use in agriculture. The objective of the study was to reuse the sludge for nutrient recycling in agriculture as a sustainable solution towards environmental protection.

2. Materials and Methods

2.1. Site Selection for Sludge Collection. Haridwar is considered one of the holy cities of India. Apart from pollution due to the lakhs of tourists who visit the city, Haridwar has progressed industrially too. The industrial estate of SIDCUL and the township of BHEL are some of the contributors to pollution. Jagjeetpur STP is one of the initiatives under Namami Gange to address the problem of pollution in the city [27]. The 68 MLD plant was found to be a well-functioning and maintained one in Jagjeetpur, Uttarakhand, India. It is effectively cleaning the wastewater generated from the city and its surroundings, thereby preventing pollution from numerous sources in the Ganga river. The sludge sample was collected from this STP. The location coordinates are 29°54′5.5548″ N and 78°8′15.6084″ E. The plant came under working conditions in June 2020. The total treatment capacity of the plant is 68 million liters per day (MLD), and it uses sequential batch reactors for the treatment process. The average sludge production reported for April 2021 was 399 MT [28]. During our inspection of the site on February 8, 2022, and February 15, 2022, we found no tertiary treatment to be taking place at this plant. The average sludge production per day at the plant was approximately 19.68 MT. Moreover, we observed that the sludge generated from the plant was deposited within the plant premises near the Ganga Riverbank. It was found that the untreated sludge was supplied to farmers only on their demand for usage as an agricultural input.

The data for the wastewater parameters of the inlet and outlet of the STP as tested at the site were obtained. The data were collected from January 2022 until mid-February 2022 after analysis by the auto-analyzer and rechecked manually at the STP. Regarding sewage, the data on solid particles (in %) in the outlets of seven centrifuges for the period of January, 2022 were also collected from the plant. The geometric mean of the solid particles in the different centrifuge outlets was calculated and plotted to describe the central tendency of the time series. The extent of the dewatering of the sewage could be understood from that information. The data for mixed liquor suspended solids (MLSS) in the six basins of the sequential batch reactor were also obtained for January 2022, which indicated the extent of suspended solids in the sequential process and the extent of purification taking place after the wastewater crossed each basin.

2.2. Sample Collection and Characterization. The sludge sample was collected in bulk using aseptic techniques, transferred to sealed packets and brought to the laboratory. The physicochemical characterizations like moisture content, total organic carbon, pH, C/N ratio, total nitrogen content, total phosphate content, total potassium content (K_2O), and total NPK were measured sequentially. The metal content was analysed using atomic absorption spectroscopy (Shimadzu-AA-6880). 12.5 gm of the sludge sample was mixed with 25 ml of DTPA reagent and placed on the shaker at 89 rpm for two hours. After this, the solution was filtered through acid-washed, distilled water-washed Whatman number 1 filter paper. The clear solution obtained was used for the analysis. All procedures for the measurement of the different parameters mentioned above were obtained from the protocols given in the fertiliser control order (FCO), 1985 [29]. A comparative assessment was done for the metal, macro-, and micronutrient content of routinely prepared compost from farmyard manure and compost from STP sludge to understand the nutrient status as well as the heavy metal status. This was done to understand its applicability for agriculture.

2.3. Product Preparation. There are a few tested products by Patanjali Organic Research Institute (PORI) that are used as organic fertiliser inputs in agriculture. They are prepared by mixing the individual components in a fixed ratio, which has been deciphered through experimentation and trials. The products contain compost as one of the components, which is prepared at the institute from farmyard manure. The products are developed with the purpose of increasing agricultural productivity and are in large demand by farmers in India. In order to take a step forward in the management of the large quantities of sludge produced at wastewater treatment plants while conforming to environmental parameters and increasing agricultural productivity, PORI has attempted to make organic fertiliser from STP sludge. Two different products, Jaivik Poshak and Jaivik Prom have been prepared by using STP sludge from Jagjeetpur instead of in-house compost.

The first one, Patanjali Jaivik Poshak, is a mycorrhiza-based patented (Patent application number 201811028449) granular biofertiliser that contains a small but powerful nutrient nanocompound mixture. It contains humic acids, amino acids, sea grass, certain primitive herbs, and natural ingredients for plant growth promotion as well as for boosting plant immunity. A modified version of the existing product was prepared by replacing the routinely used in-house compost with compost prepared from STP sludge. All other ingredients and the proportion in which they were mixed remained unchanged. The mixture was made for a total of 10 kg.

The second product is Jaivik Prom (patent application number 201811028448). It is a phosphorous-rich organic farming input that contains 10.42% to 12% phosphorous. Paddy, maize, wheat, sugarcane, potato, soya, groundnut, peanuts, onions, and numerous vegetables, legumes, fruit, flowers, and medicinal plants can all benefit from the application of this product. This particular product has also been prepared by substituting the farmyard manure compost with STP sludge compost. No changes were made to the other ingredients or the proportion of mixing. The final 10 kg product thereby prepared was compared with the original product.

2.4. The Effect of Products on Soil and Plant Germination. Both products are for agricultural use. Thus, the ultimate effect of the application of the modified products on the soil as well as the germination of plants was tested. Jaivik Poshak and Jaivik Prom as well as the modified versions of both of them were mixed with soil at the recommended dose. The soil mixtures were taken in small paper cups in fixed amounts, and in each cup, tomato seeds were sown. For each treatment, 10 cups were taken. For instance, ten cups of the soil mixture with Jaivik Poshak were taken. Similarly, ten separate cups were taken for the Jaivik Prom, and so on. The cups were placed in a randomised block design in a tray and placed in the shade. The germination was checked until the sixteenth day after sowing. On the sixteenth day, the germination percentage was calculated for individual treatment sets by using the following formula:

$$\text{Germination (\%)} = [(A/B) * 100], \tag{1}$$

where A = number of seeds germinated and B = total number of seeds sown.

Different sets of treatments along with the abbreviation for the respective sets are shown in Table 1.

In order to understand the effect of amended products on soil, the nutrient status in soil and metal concentrations were analysed [30].

2.5. Statistical Analysis. The obtained data were graphically represented as the mean ± SD. The differences between each set upon application of different fertiliser sets were validated by a two-way ANOVA followed by Tukey's range test. The Tukey's range test is performed to find means that differ significantly between them. Prior to the test, the normality of

Table 1: Different fertilisers used on soil along with their respective abbreviations.

Serial number	Treatment set	Abbreviation
1	Control	C
2	Normal Jaivik Poshak	NJP
3	Modified Jaivik Poshak	MJP
4	Normal Jaivik Prom	NJPR
5	Modified Jaivik Prom	MJPR

the data was checked and validated. The graphical representation and statistical analysis were performed using GraphPad Prism 8.0.2. For the principal component and hierarchical analysis, Z score normalisation was done for each factor. The calculation of Z score values was done using the following formula:

$$\text{Z score value} = \left\{\frac{(x-\mu)}{\sigma}\right\}, \tag{2}$$

where x is the absolute value, μ is the mean value, and σ is the standard deviation value.

3. Results and Discussion

3.1. Sampling Site. The representative images of the STP plant are shown in Figure 1.

The data on solid particles (%) in each centrifuge outlet, which is an indicator of the extent of dewatering for January 2022, were obtained from the head engineer and has been given as Table S1 in the supplementary material.

The geometric mean of solid particles generated from the seven centrifuge outlets was plotted as a time series, which is shown in Figure 2.

From the time series plot, it is evident that there are certain ups and downs, as the geometric mean of seven outlets has been taken, but the overall efficiency of dewatering is within a range of 22.24 to 28.09%, which is a very small range. The standard deviation is also very low with a maximum value of 4.78. It can be deciphered that the working efficiency of the plant is very high, and all centrifuges are working at comparable efficiencies. The data over a month in this range also state that the sludge generation capacity is also optimal. Data for MLSS (mg/L) in the six basins of the SBR in January 2022 are given in Table S2 in Supplementary Material. The mean value of MLSS in each basin along with the standard deviation was plotted and is shown in Figure 3.

From the figure, it can be seen that there is a sequential increase in the MLSS values in the six basins except for a slight fall in basin 3. Again after that, the MLSS values continuously increased and basin 6 has the highest MLSS value, which is the normal case for an SBR. As the wastewater purification proceeds in a stepwise manner, the water content is sequentially removed, and increasing amounts of solids accumulate, and hence the first basin shows the minimum MLSS concentration while the last shows the maximum value. The performance of the plant over the month was highly stable and efficient.

3.2. Sample Characterization. The routinely prepared in-house compost and the compost prepared from STP sludge were characterized simultaneously to compare their characteristics. The STP sludge had certain undesirable components, like grass, which could create problems in the final product. The unwanted particles were removed from the sludge before it was sent for product formation. The components of the two products, including sludge, are separately dropped onto the conveyor belt, which ultimately goes into the granulation drum for proper mixing in a definite ratio. All the components are mixed properly in the presence of moisture to form granules. The premix granules are then moved into the heating drum at a fixed temperature. After this, the granules are moved further into the cooling drum and dried in the presence of air. The detailed components and temperature of heating are not disclosed here, as they are patented. The comparative analysis of the in-house compost and STP sludge compost, along with the prescribed specifications as per FCO, 1985 is given in Table 2.

From the above comparative analysis, it is evident that there are a few parameters where the STP compost is not as good as in-house compost and vice versa. The moisture content is way higher for the STP compost than the prescribed limits, as stated in Table 2. The major reason for this is that the sludge was collected on a rainy day while it was lying open in the plant, thereby making it wet. However, this can be easily managed with routine drying technologies. The organic carbon content is above 15% for both in-house and STP sludge compost, with the specification of 14%. Interestingly, the pH of the sludge compost is within the prescribed specifications compared to the pH of the in-house compost. This is beneficial as it would not require external additions to bring the pH within the limit, thereby saving cost and preserving the physicochemical nature of the compost. The C/N ratio for the sludge compost is much higher than the specification, which is due to the low N content. It can be seen that the N content in the sludge compost is just marginally higher than the prescribed specification, but the in-house compost is of better quality in this respect. The phosphate content is almost double the specification in the case of sludge compost. The phosphate content is approximately 0.8% for in-house compost, compared to a specification of 0.5%. The potassium content of STP sludge compost is way lower than the recommended specification. The in-house compost also does not contain the desired concentration. The total NPK content is also lower than the specifications and other organic fertilisers for

Figure 1: Representative images of Jagjeetpur STP.

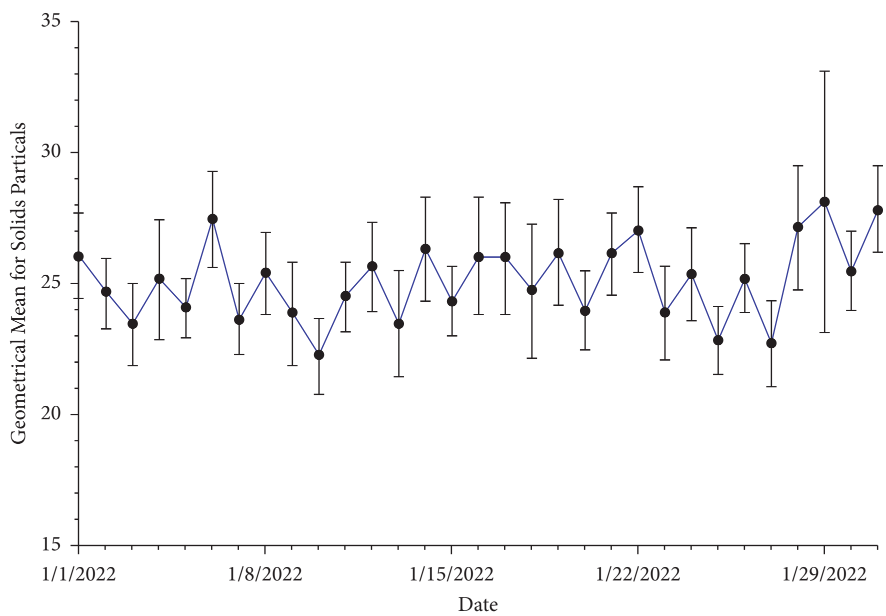


Figure 2: Time series plot of the geometric mean of the solid particles in different centrifuge outlets.

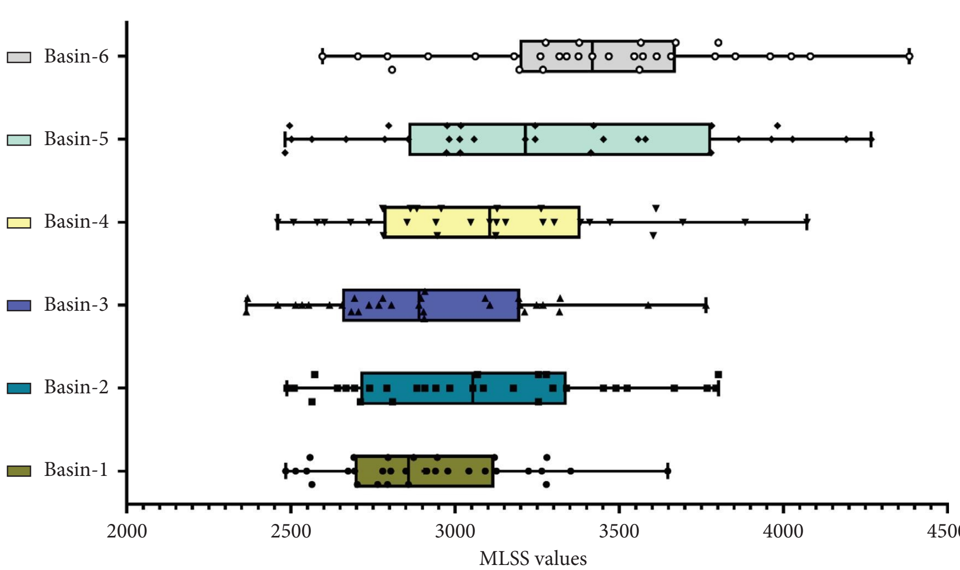


Figure 3: Average MLSS values in January 2022 in the six basins of the SBR.

Table 2: Comparative analysis of in-house sludge and STP sewage sludge compost.

Parameter	Specification	Concentration in in-house compost	Concentration in STP compost
pH	6.5–7.5	7.56 ± 0.3	6.78 ± 0.16
Moisture content (%)	15–25%	30.55 ± 0.49	52.11 ± 2.3
Total organic carbon (%)	Minimum 12%	15.24 ± 1.9	15.02 ± 1.02
Total nitrogen (N)	Minimum 0.8%	0.96 ± 0.07	0.59 ± 0.03
C : N ratio	Less than 20	15.91 ± 1.01	25.45 ± 1.83
Total phosphate as P_2O_5 (P)	Minimum 0.4%	0.77 ± 0.03	1.01 ± 0.08
Total potassium as K_2O (K)	Minimum 0.4%	0.37 ± 0.07	0.16 ± 0.06
Total NPK nutrient	Not less than 3%	2.1 ± 0.08	1.77 ± 0.06

both in-house and sludge compost [31]. Overall, we find that the STP sludge contains a number of valuable nutrients. Most of them are in concentrations greater than the desired specifications. The main aim of this study is to determine how the sludge compost could be utilised for agricultural purposes. This would help in utilising the plant nutrients present in the sludge that are usually lost. The optimised method for fortifying sludge with other amendments is to be tested in order to understand the changes brought about in sludge compost and whether it is suitable for plant application. The fortification process could help overcome the drawbacks present in the compost prepared from STP sludge and make it applicable for agricultural use. Iticescu et al. [32] showed that sewage sludge does contain agricultural nutrients like nitrogen in different forms (ammonia, nitrate, and nitrite) and phosphorous that make it suitable for use as fertiliser. The quarterly average values of heavy metals were also found to be safe and within permissible limits.

The comparative results of metals, macronutrients, and micronutrients present in both types of compost are shown below. The metal content is given in Table 3, whereas the nutrient status is given in Table 4. The specifications for metal and nutrient content as per fertiliser control order (FCO), 1985 [29] have also been shown.

The metal concentrations in the sludge are well below the permissible limit except for mercury. The concentration of mercury is 0.67 in STP sludge compost which is higher than the prescribed specification but lower than the concentration of routinely used compost, which is 1.39. Appropriate fortification of the dried sludge not only helps in reducing the metal content by dilution procedure but also helps in significantly improving its quality for usage in agriculture. The comparison of the macro- and micronutrients is given in Table 4.

The macronutrient and micronutrient status of both composts shows that there are sufficient amounts of plant macronutrients present in the STP sludge, with a great potential for utilization in agriculture. The concentrations of boron, zinc, copper, and nickel are higher than the STP sludge, while the concentrations of the rest of the nutrients are lower in comparison to the routinely used in-house compost. The status of these ingredients and the product quality would change further after the fortification process.

3.3. Effect on Soil Parameters. As mentioned earlier, the current study aims to understand the effect of the application of agricultural products made with STP sludge compost on soil characteristics as well as plant germination. The physicochemical parameters that are important for plant growth, like available nitrogen, available phosphorous, available potassium, total organic carbon, as well as heavy metal content, were measured for the soil to which the routinely used STP sludge compost was applied with respect to control soils to which nothing had been added. This would confirm the ability of the amended products to bring about faster germination as well as the effects it has on soil properties, and if at all, this could be proposed as a solution for sludge management. Table 5 shows the data for the results of physicochemical parameters for the different treatments of the soil.

The data for pH shows that the soil pH remains within the desirable range of 6.5 to 7.5 for almost all treatments. This may be possible due to the fact that all the organic products developed from the sludge are within the prescribed limit, and hence their application to the soil does not cause major pH changes. Application of MJPR and NJP to the soil brings about changes to the soil pH that are outside of the range but so minor that they are negligible as such changes are also observed for the untreated control set. This suggests that the application of such fertilisers to the soil would not require additional amendments to adjust the pH, thereby preserving other soil nutrients.

The organic carbon percentage of soil indicates the amount of organic nutrients present in the soil. Organic carbon values below 0.4 are considered low, 0.4 to 0.75 to be medium, and greater than 0.75 to be high [30]. The maximum organic carbon content was found to be present in the soil to which MJPR had been added, followed by NJPR and NJP-amended soil. This implies that the application of organic fertilisers over the long run is beneficial for building up the organic nutrient content in the soil. The untreated control had low organic content values which were enhanced to medium and even high organic content levels by the various treatments made in the current study.

The electrical conductivity of soil is an indicator of the availability of nutrients in the soil. It is an indicator of the overall fertility of the soil based on the soil's ability to store

Table 3: Concentration of metals in the sludge.

Metal contaminants	Concentration of metals (mg/kg)		
	Maximum permissible limit	In in-house compost	In STP sludge compost
Arsenic	10	3.77 ± 0.72	3.00 ± 0.05
Cadmium	5	0.65 ± 0.09	0.84 ± 0.07
Mercury	0.15	0.67 ± 0.02	1.39 ± 0.04
Lead	100	13.18 ± 0.12	18.01 ± 0.17
Chromium	50	10.61 ± 0.26	14.15 ± 0.97

Source of specification: fertiliser control order (FCO), 1985 [29].

Table 4: Comparative analysis of nutrients in STP sludge compost and farmyard compost.

Metals	Concentration of metals (mg/kg)	
	In-house compost	STP sludge compost
K	5171.93 ± 13.01	2858.95 ± 12.19
Na	1764.79 ± 17.34	1162.75 ± 9.88
Ca	1999.02 ± 11.23	1655.58 ± 8.63
B	13.23 ± 0.78	28.92 ± 1.22
Mn	137.33 ± 2.66	115.18 ± 1.22
Fe	7836.75 ± 22.76	6169.52 ± 6.63
Co	2.36 ±0 .008	2.12 ± 0.09
Ni	7.77 ± 0.16	12.42 ± 0.56
Cu	32.09 ± 0.14	40.29 ± 1.93
Zn	156.97 ± 1.22	230.3 ± 3.65

Table 5: Physicochemical parameters of soil treated with different types of fertilisers with respect to control.

	C	NJPR	MJPR	NJP	MJP
pH	7.7 ± 0.01	6.9 ± 0.01[#]	8 ± 0.05[#]	7.7 ± 0.01	7.50 ± 05
Moisture content (%)	4.16 ± 0.01	7.46 ± 0.05[#]	6 ± 0.07[#]	3.22 ± 0.01	4.44 ± 0.03
Electrical conductivity (dS/m)	0.002 ± 0.01	0.02 ± 0.01[#]	0.01 ± 0.01[#]	0.05 ± 0.01[#]	0.67 ± 0.01[#]
Total organic carbon (%)	0.39 ± 0.1	0.64 ± 0.01[#]	0.86 ± 0.13[#]	0.55 ± 0.04[#]	0.45 ± 0.1

[#]Significant difference from the control samples as derived from one way ANOVA at 95% confidence interval ($n = 5$).

nutrients. The electrical conductivity of soil increases with the increase in soil nutrients. Electrical conductivity values below 0.8 dS/m are considered normal [30]. In the current study, all values were below 0.8, and soil treated with MJP showed maximum electrical conductivity, followed by NJP. This further indicates the ability of fertilisers amended with STP sludge compost to augment the soil nutrient status compared to all other treatments. The values of EC indicate that the application of MJP has brought about the maximum increase in the electrical conductivity of soil, which is also beneficial for nutrient uptake by plants in the soil [33].

Figure 4 shows the availability of the three most important macronutrients for plants.

It was shown that adding MJP made nitrogen much more available in the soil compared to the control ($p < 0.001$). Furthermore, both normal and MJPR treatments significantly ($p < 0.001$) raised the amount of phosphorous that was available in the soil compared to the control. Available nitrogen values below 272 kg/ha are considered low; between 272 and 544 kg/ha is medium, whereas above 544 is high [30]. All kinds of treatments

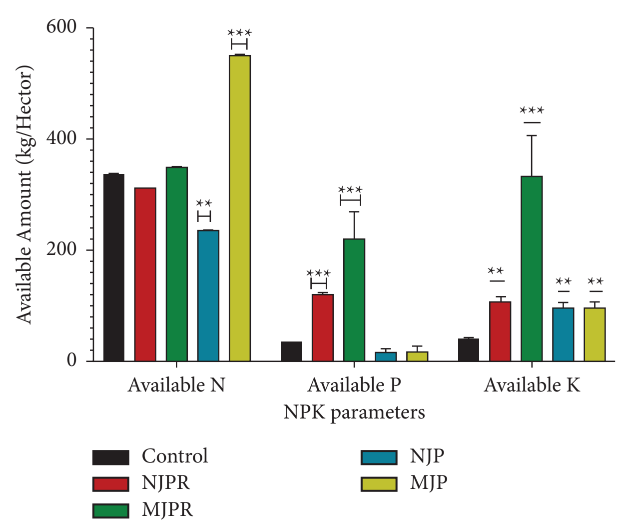


Figure 4: Availability of nitrogen, phosphorous, and potassium in soils treated with different fertilisers (the asterisks indicate significant level of difference when verified statistically for $p = 0.05$ (*), $p = 0.01$ (**), and $p = 0.001$ (***)).

increased the availability of nitrogen to medium levels, except for NJP, where the value was slightly lower than the desired levels.

The availability of phosphorous was significantly increased ($p < 0.001$) upon the application of both NJPR and MJPR and reached very high levels with respect to control. NJP and MJP-amended soil both maintained medium phosphorous levels in the soil. As per the protocol [30], available phosphorous levels of less than 12.4 kg/ha are poor, 12.4 to 22.4 are medium, 22.4–50 are high, whereas greater than 50 are very high.

Marin and Rusănescu [34] showed that sewage sludge from a sewage treatment plant in Romania when applied in different dosages (15 t/ha and 25 t/ha) brought about high yields of soybean and wheat. The concentration of heavy metals in the stem, root, and grains of plants cultivated from the soil treated with sludge were also found to be within the permissible limits. The application of sludge resulted in an improved quantity of organic matter, nitrogen, ammonium, potassium, and zinc in the soil, thus making it suitable for use as fertiliser.

Application of all four fertilisers, normal Jaivik Prom ($p < 0.01$), modified Jaivik Prom ($p < 0.001$), normal Jaivik Poshak ($p < 0.01$) as well as modified Jaivik Poshak ($p < 0.01$) significantly increased the availability of potassium in the soil. Potassium levels below 55 kg/ha are considered as low, between 55 and 135 to be medium, and above 135 to be high [30]. The moisture content of the soil was unaltered with the addition of modified Jaivik Poshak, slightly less with normal Jaivik Poshak. The moisture content almost doubled with the addition of normal Jaivik Prom and increased 1.5 times due to the addition of normal Jaivik Prom. The effect of the application of various fertilisers on soil moisture content is shown in Figure 5.

The comparative analysis of the micronutrient status due to the application of different fertilisers is shown in Figure 6.

The iron content of the soil is specific to different regions and has been stated to have a positive impact on the dry weight of plants [35]. The optimal value of iron in the soil depends on the region as well as on the plant that is grown in that particular soil. Application of MJPR and NJPR was seen to bring about the most significant change in the soil iron content ($p < 0.001$) with respect to the untreated soil in the control set. There was no statistically significant change brought about in copper and zinc content due to any of the fertiliser applications. Manganese concentration increased significantly ($p < 0.001$) due to the application of all four fertilisers.

As stated earlier, one of the major issues with using compost made from sludge is the presence of heavy metals which get deposited in the soil and ultimately land up in the food chain. Therefore, quality check and safety validation are required to assess the metal levels before it can be used for agricultural purposes. The heavy metal level in soil after the mixing of different fertilisers with soil is shown in Figure 7. (The asterisks indicate a significant level of difference when verified statistically for $p = 0.05$ (*), $p = 0.01$ (**) and $p = 0.001$ (***)).

On verifying the levels of metals within the permissible limits as prescribed by FCO, it was found that the metal concentrations were all within the limits for all kinds of fertiliser applications except for cadmium on the application of the normal Jaivik Prom, which contained 11.35 ppm of metal. The permissible limit for cadmium is 5 ppm. The level of mercury for all treatments was below the level of quantification, i.e., it was below 0.1 ppm, whereas the permissible limit for mercury is 0.15 ppm. This fact further confirms that the fortification process, in addition to the dilution brought about by the mixing of other ingredients with the compost from STP sludge, has brought the heavy metal concentrations within the permissible limits. This is possible with the use of the large amounts of sludge produced at the STP while enhancing crop productivity by promoting soil health in a natural way. It could be stated as the best reuse process for STP sludge [34, 36].

3.4. Effect on Seed Germination. Figure 8 shows the germination percentage of tomato plants in soil treated with different fertilisers.

From the data on germination percentage, it was observed that 100% germination occurred with the application of modified Jaivik Poshak. 91% germination occurred due to the application of normal Jaivik Prom followed by modified Jaivik Prom which brought about 82% germination like the control set. Regression analysis was carried out in order to understand the parameter having maximum influence on the percentage of germination. Figure 9 shows the regression analysis of parameters such as available phosphorous, available nitrogen, available potassium and concentrations of Cu, Fe, Mn, and Zn, electrical conductivity, pH, and total moisture content against germination percentage.

Figures 9(a)–9(i) show the results of regression analysis on various factors on germination percentage to understand their individual influence. It was seen that only nitrogen has a strong influence on germination percentage in the current study.

The above data was verified further by conducting principal component analysis. It was found out that the availability of nitrogen was the principal component that increased the percentage of germination (Figure 10). Compared to other factors which showed almost no influence on germination, the factor of electrical conductivity was considered important after nitrogen availability. This also suggests that appropriate availability of nutrients, not only higher nutrient concentration, was important for increasing the percentage of germination.

When the factors were clubbed together in order to understand their phylogenetic relation, a similar observation was noted. Germination percentage and the factors available—nitrogen and electrical conductivity—were close together while all other factors were distantly apart and clubbed separately, showing their proximal and distant relationship, respectively (Figure 11).

After this, the hierarchical relationship between the five different types of soil treatment was studied. It was seen that NJP and MJP clustered together and were the farthest apart

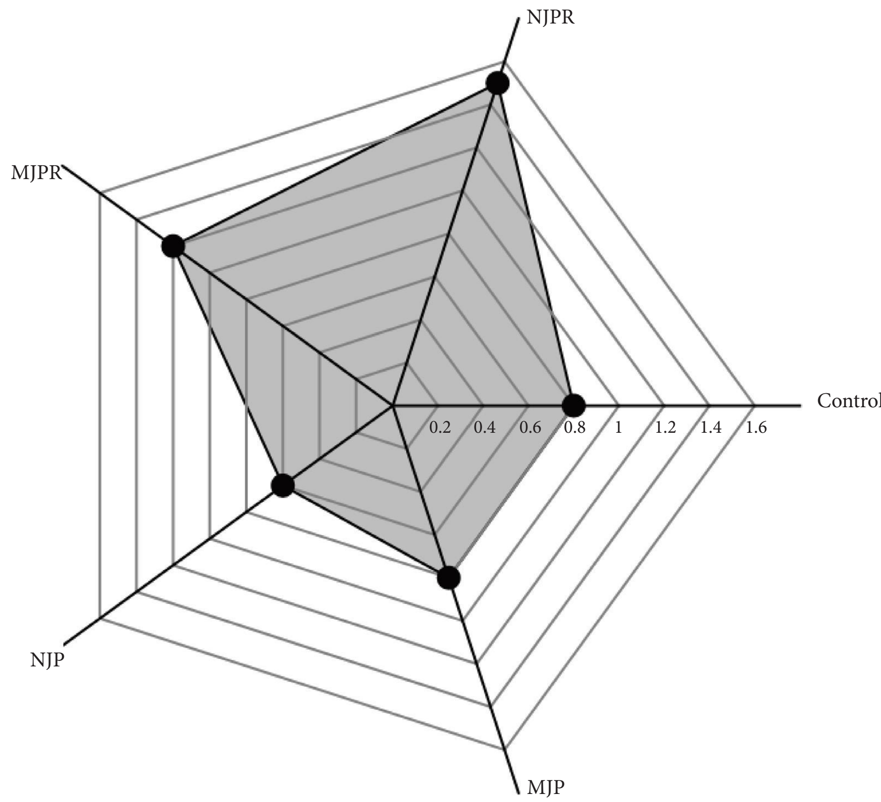


Figure 5: Application of different fertilisers and its effect on the moisture content of the soil.

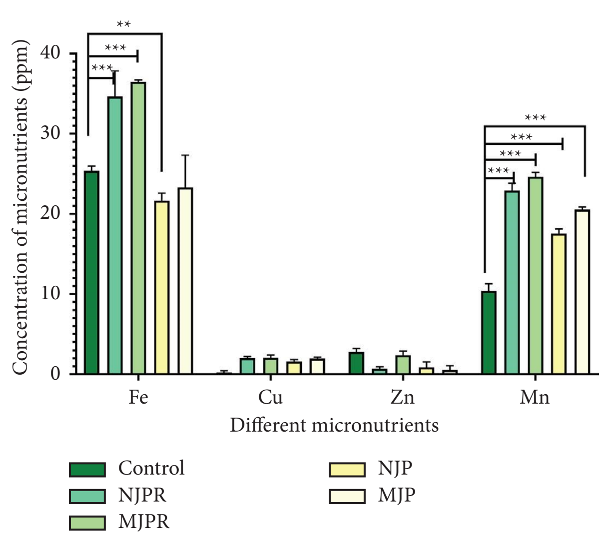


Figure 6: Effect of application of different fertilisers on the micronutrient status of soil (The asterisks indicate significant level of difference when verified statistically for $p = 0.05$ (*), $p = 0.01$ (**), and $p = 0.001$ (***)).

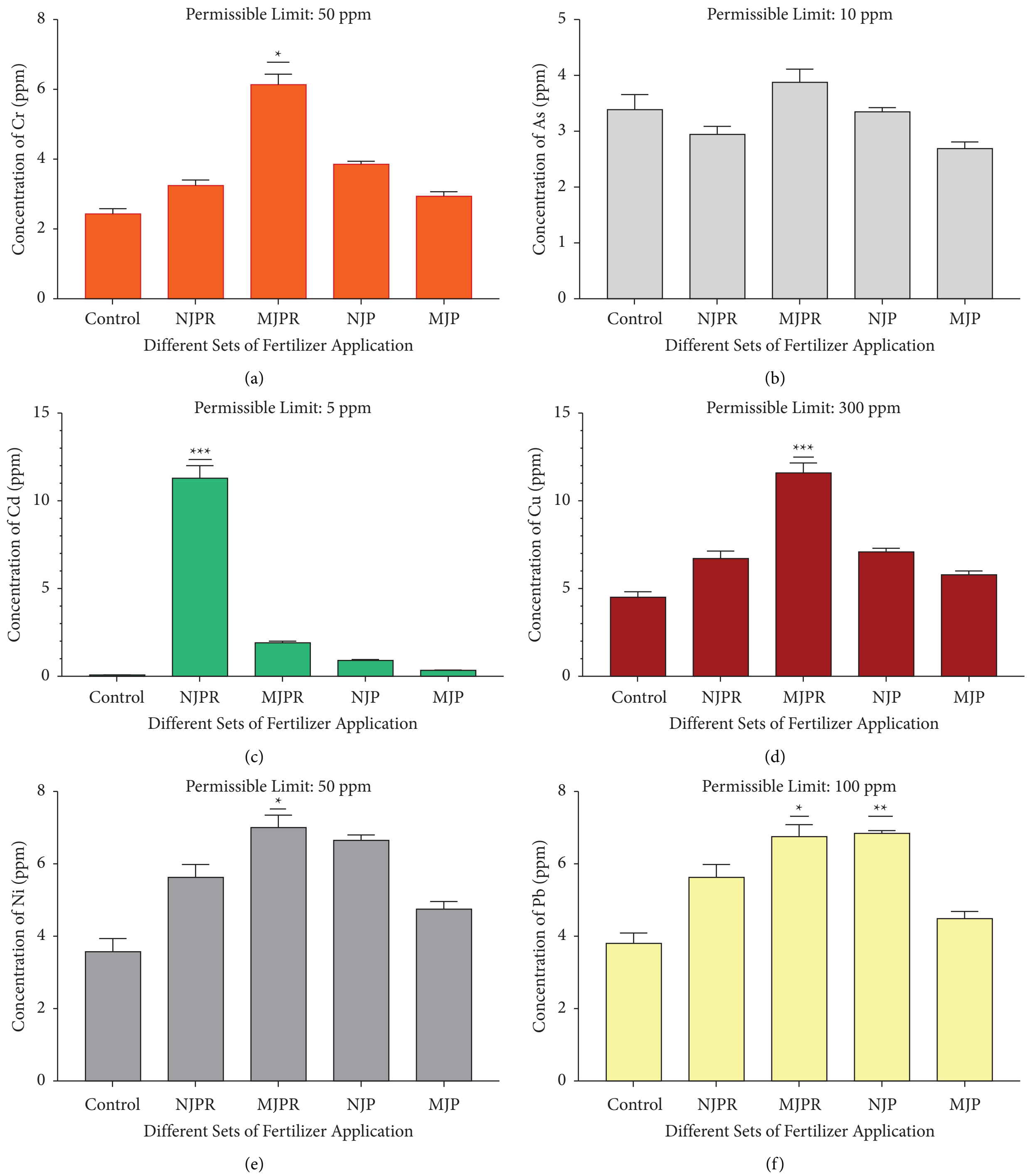
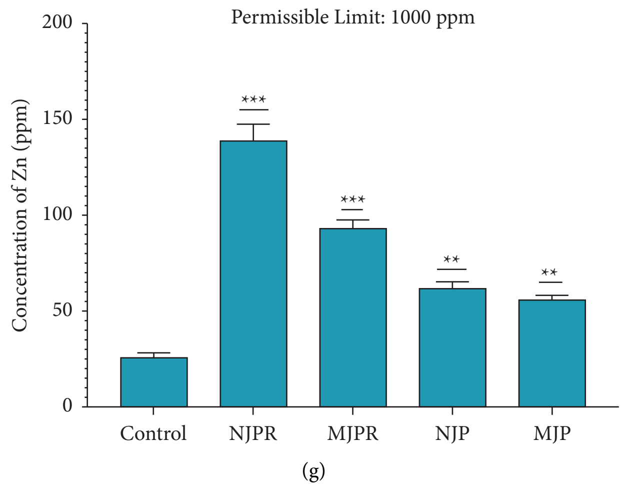


Figure 7: Continued.



(g)

Figure 7: (a) Concentration of chromium in soil after different kinds of treatment. (b) Concentration of arsenic in soil after different kinds of treatment. (c) Concentration of cadmium in soil after different kinds of treatment. (d) Concentration of copper in soil after different kinds of treatment. (e) Concentration of nickel in soil after different kinds of treatment. (f) Concentration of lead in soil after different kinds of treatment. (g) Concentration of zinc in soil after different kinds of treatment.

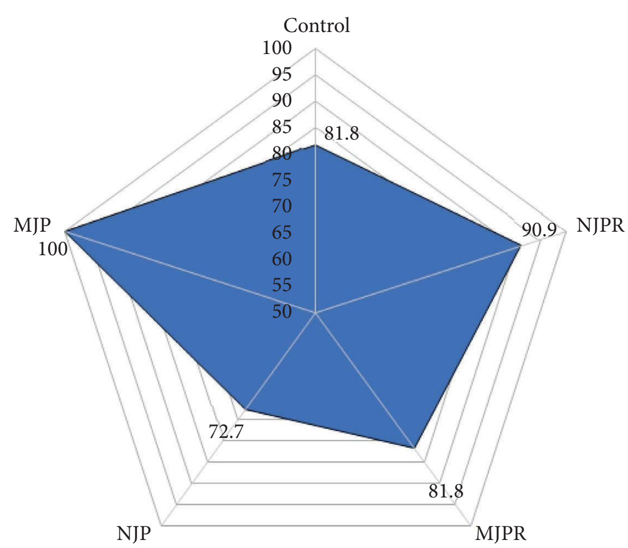


Figure 8: Germination percentage of tomato seeds upon different kinds of treatment.

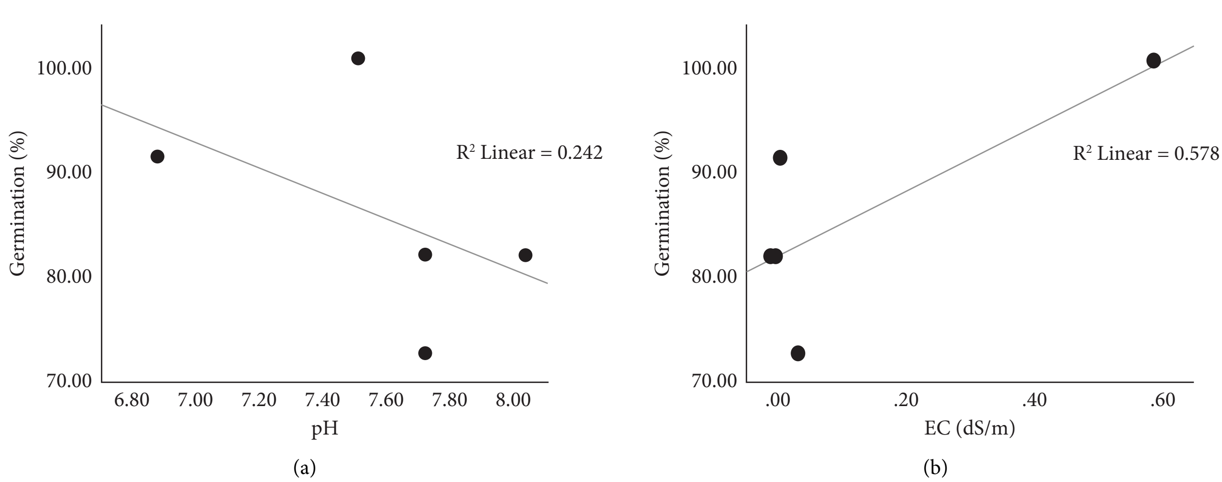


Figure 9: Continued.

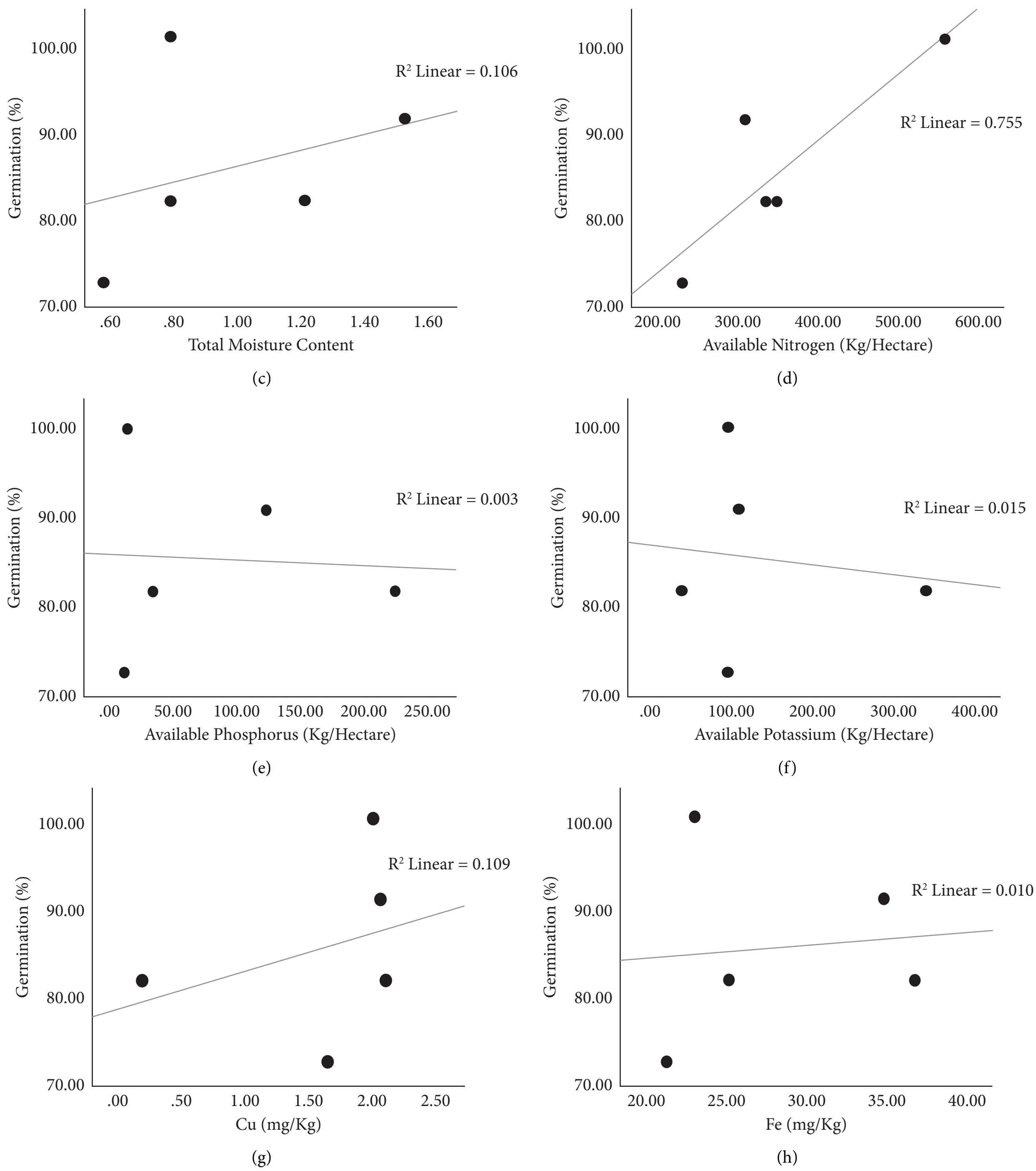
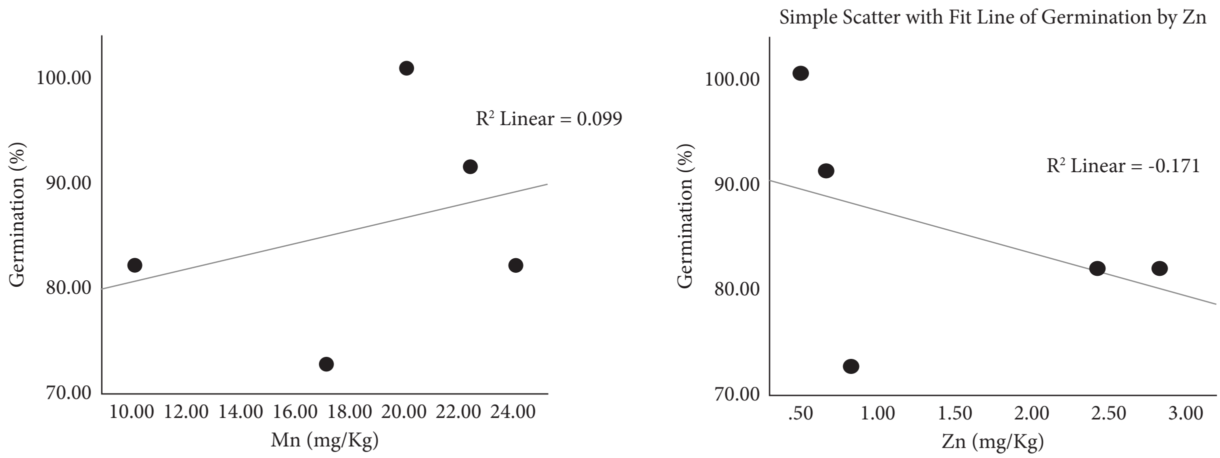


Figure 9: Continued.



(i) (j)

Figure 9: (a) Germination percentage at different pH values indicates no direct relation between the two parameters. (b) Electrical conductivity of soil has no direct impact on the germination percentage. (c) Total moisture content has minimal impact on germination percentage. (d) Greater availability of nitrogen improves germination percentage. (e) Availability of phosphorous has minimal impact on germination percentage. (f) Availability of potassium has minimal impact on germination percentage. (g) Availability of copper has minimal impact on germination. (h) Availability of iron has minimal impact on germination. (i) Availability of manganese has minimal impact on germination. (j) Availability of zinc has minimal impact on germination.

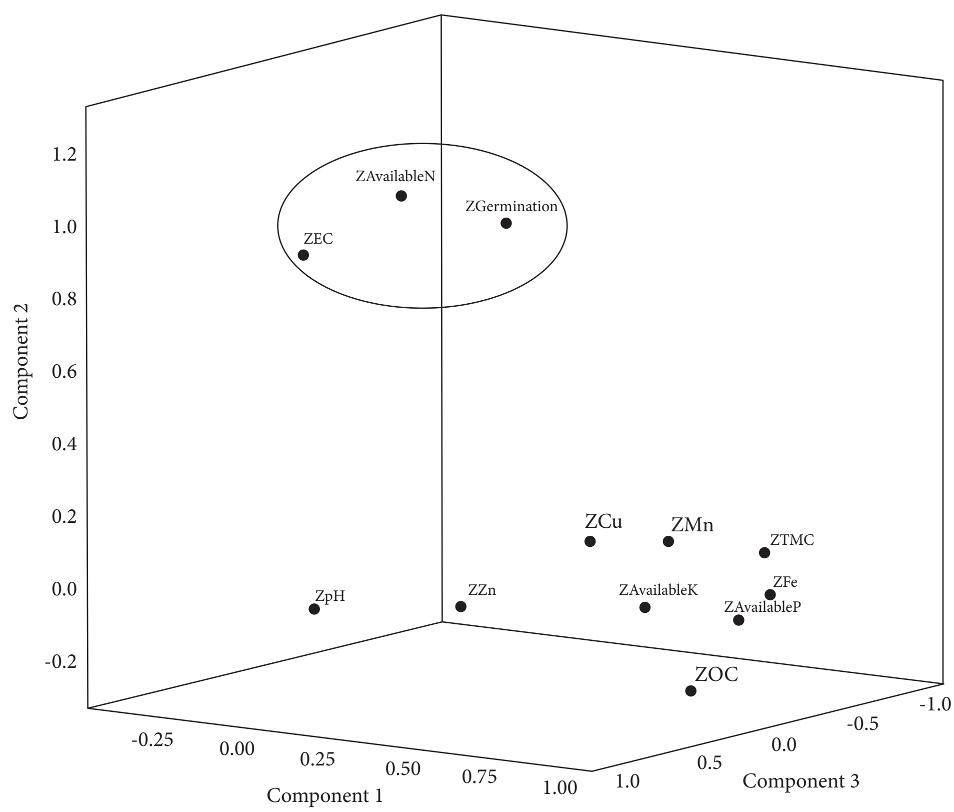


Figure 10: The principal component analysis showing that availability of nitrogen is the principal factor that promotes germination of seed. The second most important factor was electrical conductivity of soil.

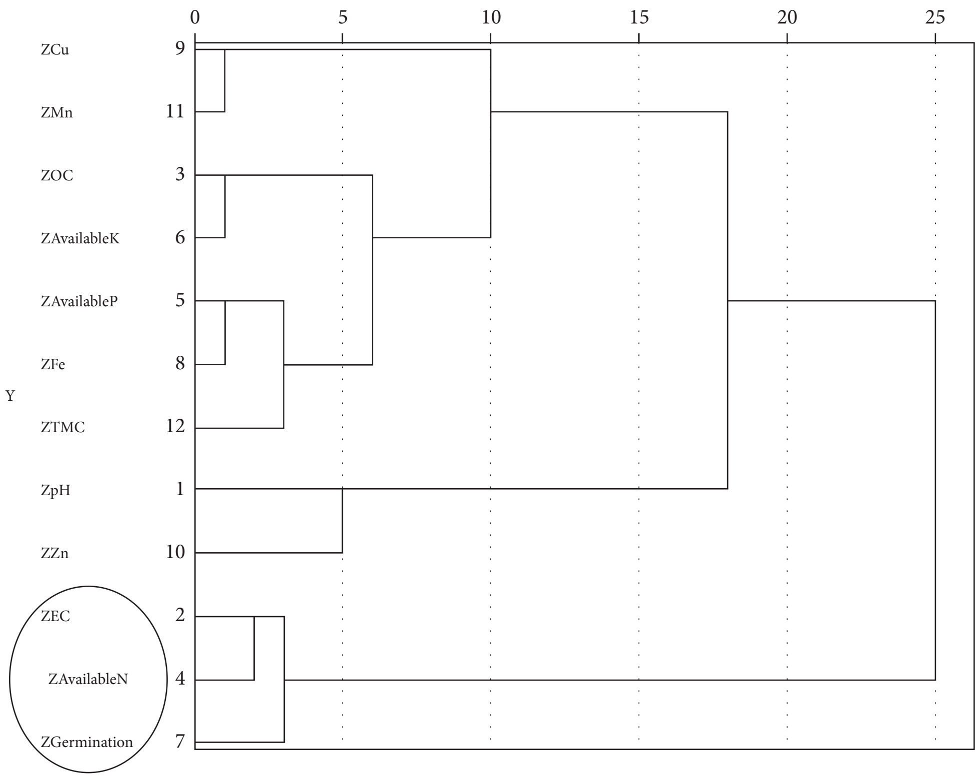


Figure 11: Hierarchical relationship between the different factors shows that the maximum influence of available nitrogen for increasing the percentage of germination.

from control. NJP was most similar to the control set, and MJP was moderately similar. This shows the close similarity between Jaivik Prom and its effect on the soil parameters as well as seed germination. On the other hand, MJP was another distinct treatment that also showed influence on certain other soil physicochemical nutrients and hence remained as a separate branch in the tree.

4. Conclusion

With increasing volumes of sludge, there is a dire need for sludge management. Sludge obtained from the Jagjeetpur STP was tested and found suitable as an organic input in agriculture. Two products, Jaivik Prom and Jaivik Poshak, were developed from the sludge after replacing composted cow dung manure with sludge after prior analysis. Jaivik Poshak was found to be effective in maintaining soil pH, increasing electrical conductivity, and increasing available nitrogen content. The concentration of the micronutrient manganese was also found to be enhanced, and heavy metal concentrations were within the prescribed limits. The added advantage of the application of this product was that it brought about 100% germination of tomato seeds within sixteen days. The other product, Jaivik Prom, increased the organic carbon content and available phosphorus and potassium content of the soil. Thus, it can be said that both the products amended with STP sludge compost bear plant nutritional value. Future studies on the effect of agricultural productivity and comparison of results with those of chemical fertilisers would answer questions on the use of such products. The results of this study can be proposed as a sustainable solution for sludge management with minimal energy input and high-end machinery. Moreover, the sale of these reputed products can bring revenue for the company and gains for the farmers. Thus, it is a true situation of the conversion of waste to wealth.

Data Availability

The data supporting the conclusions of this article are included within the article. Any queries regarding this data may be directed to the corresponding author.

Disclosure

The paper had been uploaded as a preprint on authorea at https://www.authorea.com/users/473470/articles/563673-reuse-of-sewage-sludge-as-organic-agricultural-products-an-efficient-technology-based-initiative.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Acharya Balkrishna conceptualized the study and involved in funding acquisition. Srimoyee Banerjee and Sourav Ghosh curated the data and performed formal analysis. Vedpriya Arya investigated, supervised, and validated the study and administered the project. Divya Chauhan and Ilika Kaushik proposed the methodology. Acharya Balkrishna and Vedpriya Arya collected the resources. Sourav Ghosh developed software. Sumit Kumar Singh performed visualization. Srimoyee Banerjee wrote the original draft. Vedpriya Arya, Srimoyee Banerjee, and Sourav Ghosh wrote, reviewed, and edited the study.

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Supplementary Materials

Table S1 in the supplementary material shows the percentage of solid particles present in the different centrifuge outlets of the sequential batch reactors. The consistency of the results can be seen in the data which indicates the stable performance of the reactors in the sewage treatment plant. Table S2 in the supplementary material shows the proportion of mixed liquor-suspended solids present in the different basins or aeration tanks of the sewage treatment plant. An increasing trend in the concentration of the MLSS in found in basin 1 to basin 6, which is a typical representation of the functioning of a STP. (*Supplementary Materials*)

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