

Effect of Municipal Sludge on Soil Properties and Tree Nutrient Status

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ABSTRACT

The present investigation was carried out to study the nutritional status of soil and tree species using sludge. The research was conducted at Punjab Agricultural University in collaboration with the State Forest and Wildlife Preservation Department at Forest Nursery Baddowal, Ludhiana. Sludge from different sewage treatment plants was used as an organic amendment. The main plot treatments included sludge from three sites (Bhattian, Balloke, Jamalpur) and a control (no sludge), and the sub-plots included three forest tree species: *Terminalia arjuna* (Arjun), *Eucalyptus* clone 413 (Safeda), and *Melia composita* (Dek). Different soil macro- (phosphorus, potassium) and micro-nutrients (zinc, iron, manganese), as well as organic carbon, electrical conductivity, pH, and dehydrogenase activity, were analyzed in the soil after twelve months. The Arjun plants led to the highest improvement in soil macro- and micro-nutrient levels when grown with sludge from Bhattian, as compared to sludge from Balloke and Jamalpur. Plant macro- (nitrogen, phosphorus, potassium) and micro-nutrient (zinc, iron, manganese) contents were higher in sludge-treated soils (notably Bhattian) than in the control. Overall, sludge application significantly enhanced soil fertility and the nutrient uptake of tree seedlings, with Arjun showing the greatest nutrient accumulation among the species.

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1. INTRODUCTION

Municipal solid waste generation is rising rapidly with urbanization, creating significant disposal challenges [49]. A promising strategy for managing organic waste, including sewage sludge, is to recycle them as soil amendments for plant growth [12]. Such recycling not only addresses waste disposal but also helps restore degraded soils by returning organic matter and nutrients to the land [14], [54]. Municipal wastewater and sludge contain valuable organic matter and plant nutrients (notably nitrogen and phosphorus) that can be recovered and utilized for agronomic benefit [31], [50]. Using these materials in agriculture and forestry thus offers dual advantages: safe waste reutilization and enhanced soil fertility leading to improved plant productivity [24], [11], [25], [3].

Many studies have demonstrated that amending soil with organic waste or sewage sludge can significantly improve soil properties and boost plant growth. The addition of such amendments increases soil organic matter content, which in turn improves soil structure, water-holding capacity, and nutrient availability [2], [26]. For example, the use of treated municipal effluents and sludge in irrigation has been reported to elevate soil fertility and crop yields due to their high nutrient and organic content [24], [25]. Sewage sludge is rich in macronutrients and micronutrients and can be applied to soil either directly, after appropriate treatment, or in composted form [22], [10]. As the organic fraction of sludge decomposes, it is largely converted into stable humus that increases the soil's cation exchange capacity and overall nutrient retention [22]. Accordingly, several authors have noted that sewage sludge application improves soil physical, chemical, and biological characteristics, ultimately enhancing plant nutrition, biomass production, and yield [11], [3], [25], [19]. In nursery practice, organic waste-based substrates (including sewage sludge) have been used as a low-cost alternative to mineral fertilizers, often yielding better seedling quality and growth [19], [8]. Nutrient uptake from such waste amendments can supply ample nitrogen, phosphorus, and other essential elements to plants, thereby promoting vigorous growth and higher biomass accumulation [31].

Despite these benefits, there is limited information to date on the specific effects of sewage sludge amendments on the nutritional status of tree species such as *Eucalyptus*, *Melia*, and *Terminalia*. These trees — for instance, *Eucalyptus tereticornis*, *Melia composita*, and *Terminalia arjuna* — are fast-growing species valued for timber, agroforestry, and landscaping uses. They are increasingly planted in afforestation and plantation programs to meet rising demand for wood and to rehabilitate degraded lands. It is hypothesized that recycling organic waste like municipal sludge into the cultivation of these species could improve seedling growth and nutrition while contributing to sustainable waste management. Therefore, the present study was undertaken to evaluate the effect of municipal sewage sludge on soil fertility and the nutrient status of these three tree species. By assessing parameters of soil quality and plant nutrient uptake, this work aims to determine the potential of municipal sludge as a nutrient-rich amendment for enhancing tree growth, thus providing a basis for its safe and effective use in forestry and plantation management [52], [49].

2. LITERATURE REVIEW

Soil Fertility

The incorporation of sewage sludge into soil has been widely shown to enhance overall soil fertility through multiple pathways. As a rich source of organic matter, sludge additions can significantly increase soil organic carbon content, which in turn improves soil structure, water-holding capacity, and cation exchange capacity. For example, [2], [26] reported that applying municipal waste compost or manure led to higher soil organic matter levels and better soil physical properties (such as aggregation and moisture retention). The gradual decomposition of sludge yields humus that augments the soil's cation exchange capacity (CEC), thereby improving nutrient retention [22]. [14] noted that various organic wastes, including sewage sludge, have a “great positive impact on soil physical, chemical, and biological properties”, ultimately contributing to greater soil fertility and crop yield. Many studies in agricultural and forestry contexts concur that recycling organic residues into soil can restore degraded soils by supplying essential nutrients and organic matter [12], [24]. This leads not only to improved soil health but also to enhanced plant productivity [24], [25]. In short, sewage sludge application tends to upgrade key fertility indicators – increasing soil organic carbon and nutrient availability while fostering a more favorable soil structure and microbial environment – all of which are integral to soil fertility.

The effects of sewage sludge on soil pH and salinity (electrical conductivity) can vary with sludge characteristics and application rates, but moderate applications generally cause only slight shifts in these parameters. In many cases, sludge amendments result in minimal change to soil pH. [56] for instance, found

no significant pH shift after applying urban sewage sludge to a calcareous soil. The high buffering capacity of organic matter can even help stabilize pH: composted sludge has been observed to ameliorate soil acidity by improving moisture retention and aeration [7], [20]. In some studies, slight pH increases (on the order of +0.5 to +1.5 units) were recorded following repeated biosolids applications to acidic soils [9]. Conversely, extremely high sludge rates or certain sludge types may induce a minor pH decline due to organic acid production and nitrification [33], [34]. Overall, under proper usage, sewage sludge tends to maintain soil pH within the neutral to slightly alkaline range, which is generally favorable for nutrient availability. With respect to salinity, sewage sludge often contains soluble salts that can raise the soil's electrical conductivity (EC). Numerous authors have documented increases in soil EC after sludge application [35- 37], [33]. [38] attributed the higher EC of sludge-amended soils directly to the salts present in the sludge. This effect is usually modest – in one study, soils receiving sewage sludge had EC values only a few dS m^{-1} higher than unamended soils, though still within agronomic tolerance [38]. Interestingly, [39] observed that soils treated with sewage sludge showed lower EC than those given equivalent amounts of chemical fertilizers, suggesting that sludge may pose less salinity risk than synthetic fertilization in some cases. In general, applying sludges at prudent rates results in a slight increase in soil salinity relative to control, and this is rarely detrimental to plants. Nonetheless, monitoring of soil EC is advisable, particularly in arid regions or under repeated high-dose applications, to ensure salt levels remain below crop injury thresholds.

Macronutrients

Municipal sludge is well recognized as a valuable source of plant macronutrients, particularly nitrogen (N) and phosphorus (P), and to a lesser extent potassium (K). Sewage sludge typically contains substantial concentrations of organic N and P from biological waste, making it an effective fertilizer or soil conditioner in place of mineral NPK fertilizers [14], [25]. Accordingly, many studies have reported increased availability of N, P, and K in soils following sludge amendments. [34] observed marked improvements in soil N and P status when sewage sludge was applied to a nutrient-poor calcareous soil, accompanied by higher N and P uptake by crops (see also Plant Nutrient Uptake below). Likewise, [40] found that amending two different soils with sewage sludge compost led to significant increases in extractable P and other nutrients, reflecting the compost's fertilizer value. Phosphorus is often a major benefit of sludge use: [41] noted that sludge contains a high proportion of organically bound P that can replenish labile P in soil over time, thereby reducing the need for imported phosphate fertilizers. In the case of K, which is present in sludge in more moderate amounts, studies still report measurable gains. [56] documented that soil available potassium increased by approximately 23–27% under sewage sludge application (versus unamended soil), and [38] similarly reported higher exchangeable K in sandy soils treated with sludge. These nutrient-rich amendments can thus supply a substantial part of crop nutrient requirements, working in a semi-arid Mediterranean setting, showed that barley yields and N–P uptake were significantly improved by sewage sludge fertilization, underscoring that sludge-derived macronutrients were readily available to plants. Similarly, [39] reported enhanced rice growth and N uptake in low-fertility soils amended with sewage sludge, as compared to unfertilized controls. In Brazil, field trials have even demonstrated that sewage sludge can partly substitute for conventional fertilizers in tree plantations: for example, Eucalyptus plantations fertilized with sludge produced wood biomass comparable to those with full mineral N and P inputs, due to the sludge's high N and P content [42]. Overall, the consensus in the literature is that sewage sludge serves as a significant reservoir of macronutrients that, when properly treated and applied, improves soil nutrient capital (N, P, K) and promotes plant growth on nutrient-deficient soils.

Micronutrients

Beyond NPK, sewage sludge also supplies important micronutrients to the soil, notably zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn), which are essential for plant nutrition. Sludge-originating micronutrients

can replenish soil pools that are often depleted in cultivated lands. Many investigations have found that sludge amendments raise the DTPA-extractable (plant-available) levels of Zn, Fe, Cu, and Mn in soils [13], [40]. For instance, [13] reported that the available zinc concentration in a sludge-amended soil was over an order of magnitude higher than in an untreated soil (762 mg l^{-1} vs. 37 mg kg^{-1} in their extraction method), illustrating the sludge's capacity to supply micronutrients. In a comparative study, [32] observed that successive annual applications of urban sewage sludge led to cumulative increases in soil total Zn, Cu, and Fe, along with organic matter, thereby improving overall topsoil fertility. Increased micronutrient availability under sludge treatment has been linked to higher uptake of these elements by plants: [4] found that crops grown on sludge-amended soil accumulated more Zn and other micronutrients in their tissues compared to those on control soil, reflecting the greater soil supply. Similarly, in a pot trial with parsley, [56] demonstrated that sewage sludge application elevated the concentrations of Fe and Mn in the soil and correspondingly in the parsley plants, without causing toxicity. These studies indicate that, in addition to macronutrients, sludge can effectively fortify the soil with trace elements necessary for plant growth. Enrichment of Zn and Cu is particularly beneficial for crops and trees in micronutrient-deficient soils, as it can prevent disorders like Zn deficiency and improve crop nutritional quality [43], [44].

However, the micronutrient-rich nature of sewage sludge comes with the caveat that some elements can become excessive or introduce environmental risks if not managed properly. The same metals that are essential in small amounts (Zn, Cu, Mn, Fe) can be pollutants at high concentrations, and sludge may also contain non-essential heavy metals such as lead (Pb), cadmium (Cd), or chromium. Long-term or high-rate sludge applications can lead to the accumulation of these elements in soil. [7] observed, for example, that increasing the application of sewage sludge fertilizer resulted in higher uptake of Zn and Cu in sunflower plants, along with slight phytotoxic effects at the highest sludge dose due to metal stress. Similarly, [33] found that sorghum grown in soils amended with different types of sludge showed variable metal uptake, indicating that sludge treatment processes influence metal bioavailability to plants. On a positive note, some studies suggest that organic amendments can immobilize a portion of heavy metals in less bioavailable forms. [2] examined a calcareous soil amended with farmyard manure and municipal compost and found that while total soil metal levels (e.g. for Zn, Cu) did increase, a large fraction of the added metals was retained in stable organic and mineral complexes, thus not immediately available for plant uptake. This immobilization effect was attributed to the high organic matter and phosphate content binding the metals. In addition, regulatory guidelines and prudent management (e.g. applying only treated sludge that meets safety standards) have been effective in keeping heavy metal additions within safe limits [14]. Indeed, [9] reported that the use of properly treated municipal sludge compost on *Mangifera* tree plots did *not* lead to any significant heavy metal buildup in the soil or plant tissue. In summary, sewage sludge generally enhances the soil's micronutrient status (Zn, Fe, Cu, Mn), which can correct micronutrient deficiencies and support plant nutrition, but careful attention must be paid to sludge quality and application rates to avoid excessive accumulation of heavy metals over the long term. When used responsibly, the net effect of sludge on soil micronutrients is predominantly beneficial for soil fertility and plant health.

Soil Microbial Activity

Augmenting soil with organic amendments like sewage sludge also stimulates soil biological activity, which is a key aspect of soil health. The added organic carbon serves as an energy source for soil microbes, leading to increases in microbial biomass and enzymatic activities [14], [31]. One commonly measured indicator of microbial activity is dehydrogenase activity (DHA), an enzyme assay that reflects the oxidative metabolism of soil microbiota [45]. Numerous studies have demonstrated sharp rises in soil dehydrogenase activity following sludge application. [46] for example, reported a 102% increase in DHA in a field soil amended with municipal sewage sludge at 5 t ha^{-1} , relative to an unamended control. They attributed this surge to the sludge's

high organic matter content, which fueled greater microbial growth and respiration. In general, dehydrogenase and other soil enzymes (such as urease, phosphatases, and β -glucosidase) show significant positive responses to organic amendments. [47] found that amending a saline, nutrient-poor soil with moderate rates of sewage sludge or compost led to substantial increases in multiple enzyme activities – including dehydrogenase, alkaline phosphatase, and urease – corresponding with an overall improvement in soil biological status. (At an excessively high sludge rate in that study, enzyme stimulation was less pronounced, likely due to osmotic stress or inhibitory effects of surplus salts/heavy metals, underscoring the importance of appropriate dosing.) The linkage between organic carbon inputs and enzyme activity is well-established: [45] noted that soil dehydrogenase activity is strongly correlated with soil organic C levels and can serve as a sensitive indicator of enhanced microbial activity after organic amendments. In addition to enzymes, microbial biomass and diversity tend to increase with sludge application. [31] observed that adding organic amendments significantly raised the microbial biomass C in soil, as well as levels of glomalin (a glycoprotein from soil fungi), indicating a more abundant and active microbial community. Similarly, a long-term field study (as cited in [14]) showed that repeated biosolid applications improved soil microbial biomass and functional diversity without harmful effects. The consensus is that by supplying readily degradable organic substrates and nutrients, sewage sludge creates a more favorable habitat for soil microorganisms, thereby boosting microbial population size and activity. This heightened microbial activity accelerates nutrient cycling (mineralization of N, P, S, etc.) and can improve soil structure (through microbial exudates and biomass contributing to aggregation), further reinforcing soil fertility. In sum, the application of sewage sludge tends to invigorate the soil food web – increasing microbial biomass and enzyme activities – which is an important benefit for sustainable soil fertility and is often used as an indicator of improved soil quality following organic amendments [46], [14].

Plant Nutrient Uptake

Improvements in soil nutrient availability and biological activity due to sewage sludge typically translate into better plant nutrition. Enhanced uptake of both macro- and micro-nutrients by plants grown on sludge-amended soils is a common finding in the literature. In general, plants in sludge-treated media show higher tissue concentrations of N, P, K and essential micronutrients compared to plants in unamended or chemically fertilized media. For instance, [5] observed that barley grown in soil amended with sewage sludge had significantly higher grain N content and yield than barley on unfertilized soil, reflecting improved N nutrition. [9] reported that tree seedlings fertilized with sewage sludge compost accumulated greater N in their leaves (approximately 12 g kg⁻¹ dry weight, versus about 8 g kg⁻¹ in control plants), along with higher P and K, which collectively led to enhanced growth and photosynthetic capacity. In a study on vegetable crops, [38] found that cucumber plants in sludge-amended plots had elevated leaf N, P, and K levels and produced higher yields compared to those in control plots, indicating more efficient nutrient uptake from the sludge-enriched soil. Similarly, effluent irrigation (which shares similarities with sludge in providing organic nutrients) has shown positive effects on tree nutrition: [25] noted that *Dalbergia sissoo* trees irrigated with municipal wastewater had significantly greater foliar N, P, and K concentrations than trees irrigated with normal water, demonstrating the fertilization value of waste-derived nutrients for plant uptake.

Sludge amendments also improve the plant uptake of micronutrients. [56] observed that parsley grown in sludge-treated soil accumulated more Fe and Mn in its edible tissues, aligning with the higher availability of these micronutrients in the soil. [4] similarly reported increased uptake of Zn and other micronutrients in crops cultivated on sludge-amended soils, without any observed toxicity, suggesting that the additional micronutrient uptake was beneficial for plant nutrition. An important consideration is the uptake of heavy metals: if present in sludge, elements like Cd, Pb, or excessive Zn could be taken up by plants to some degree. [34] examined this issue in a study on cucumber and noted that while sludge application did raise the concentrations of certain heavy metals in soil and plant tissue, the levels in the edible parts remained below

toxic thresholds when the sludge was applied at agronomically recommended rates. In fact, the improved nutrient status (NPK and micronutrients) in the plants was the dominant effect, leading to greater biomass and fruit yield. Similarly, [11] observed that fodder trees grown on calcareous soil and irrigated with treated wastewater showed higher nutrient contents and better growth, with heavy metal contents in leaves within safe limits for forage. These findings underline that, under controlled usage, sewage sludge can markedly enhance plant nutrient uptake of essential elements, thereby improve plant growth and nutritional quality, while not necessarily cause unsafe accumulation of contaminants. In summary, the use of municipal sludge as a soil amendment tends to enrich plants' nutritional status – increasing their internal pools of nitrogen, phosphorus, potassium, and vital micronutrients – which is a direct consequence of the improved soil fertility and biological activity in sludge-amended soils.

Tree Growth Response

Fast-growing tree species generally exhibit strong positive growth responses to organic amendments such as sewage sludge, thanks to the improved soil conditions and nutrient supply. While research specifically on *Terminalia arjuna* or *Melia composita* is limited, numerous studies on analogous tree species provide evidence that sludge application can boost tree growth and biomass production. Eucalyptus, poplar, acacia, and other woody species have been studied in this context. In a nursery trial, *Acacia mangium* seedlings showed significant enhancements in growth when sewage sludge was incorporated into the potting mix, achieving greater height and biomass than those grown in standard soil mix [8]. [19] similarly reported that replacing part of the mineral fertilizer with organic waste-based substrate in tree nurseries yielded seedlings with equal or superior growth and quality, highlighting sludge's potential as a nutrient source for young trees. Positive results extend to field planting as well. [24] observed that hybrid poplar clones grew more vigorously and accumulated more biomass when grown on land treated with industrial sludge (containing organic matter and nutrients) compared to untreated soil, although they cautioned that foliar heavy metal content increased in those conditions. In arid soils of India, [25] demonstrated that *Dalbergia sissoo* (shisham) trees irrigated with municipal effluent attained higher height and girth than those under freshwater irrigation, due to the supplemental nutrients and organic matter in the wastewater. This suggests that organic waste inputs can ameliorate otherwise harsh soil conditions (e.g. low fertility or salinity) and support better tree growth. [12] reported a similar trend with *Acacia nilotica* under saline conditions: the addition of municipal wastewater (rich in organic nutrients) improved seedling survival and growth as well as nutrient uptake, compared to saline water alone. These examples underscore that the growth of woody species, especially fast-growing varieties, benefits from the improved soil fertility and moisture regime brought about by organic amendments.

Notably, Eucalyptus plantations have been a focus of sludge research in forestry. In Spain, [20] evaluated sewage sludge application in a silvopastoral system with *Eucalyptus nitens* and found that the sludge provided sufficient nutrients to sustain tree growth without adverse effects on soil or herbage, effectively acting as a fertilizer. In Brazil, field trials on Eucalyptus have shown that sewage sludge can replace a substantial portion of mineral N and P fertilizers. [42] reported that 22-month-old *Eucalyptus urograndis* trees fertilized with sewage sludge (at an appropriate agronomic rate) achieved wood production and trunk growth statistically on par with fully fertilized trees, while also improving soil P availability. Such findings are significant for plantation forestry, suggesting that sludge amendments can produce timber yields comparable to conventional fertilization regimes, with the added benefits of recycling waste. Beyond Eucalyptus, other tree species respond similarly: fruit and biomass trees have both been studied. [9] showed that *Mangifera persiciforma* (a mango relative) grew taller and had greater stem diameter when grown in soil amended with municipal sludge compost, and importantly, no heavy metal contamination was observed in soil or fruit. Positive growth responses have also been documented in willows and poplars used for biomass or remediation purposes – for example, biosolids additions increased the shoot biomass of willow (*Salix* spp.) by improving nutrient uptake

and photosynthetic activity [48], and composted pulp sludge was found to boost the 17-year height increment of loblolly pine in one long-term study [23]. These studies collectively indicate that organic amendments can substantially enhance tree growth metrics such as height, stem diameter, volume increment, and overall biomass yield.

In summary, although direct literature on *T. arjuna* or *Melia* with sewage sludge is sparse, the existing body of research on fast-growing trees strongly suggests that these species would likewise benefit from sludge fertilization. By supplying a balanced suite of nutrients, improving soil moisture retention, and stimulating microbial activity, municipal sludge creates soil conditions that support vigorous tree growth. This has implications for afforestation and plantation programs: integrating sewage sludge or similar organic amendments could accelerate seedling development and productivity in forestry operations [11], [8]. In addition, using sludge in tree cultivation contributes to sustainable waste management, aligning with environmental goals.

Overall, the literature portrays sewage sludge as an effective soil amendment that can improve the growth performance of a variety of tree species (*Eucalyptus*, *Acacia*, poplar, etc.), and it is reasonable to extrapolate these benefits to other fast-growing trees like *Terminalia arjuna* and *Melia composita*. With proper treatment and application protocols, recycling municipal sludge into silvicultural systems can thus enhance tree nutrition and growth while safely disposing of organic waste – a clear win-win for agriculture and the environment.

3. MATERIAL AND METHODS

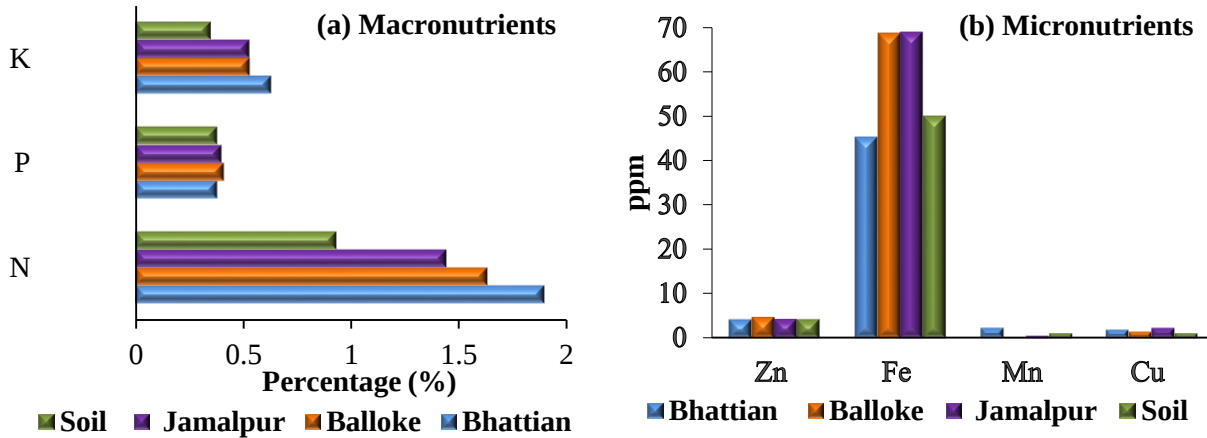
The experiment was carried out at Punjab Agricultural University, Ludhiana, in collaboration with the State Forest and Wildlife Preservation Department at Forest Nursery, Baddowal (Ludhiana). The experiment was laid out in a factorial completely randomized design. There were four main plot treatments consisting of sludge from three different sewage treatment plants (Bhattian, Balloke, Jamalpur) and a control (no sludge). The sludge was mixed into the potting soil at a concentration of 1% of the total soil weight per polybag. The sub-plot treatments consisted of three tree species: *Terminalia arjuna* (Arjun), *Eucalyptus* clone 413 (Safeda), and *Melia composita* (Dek). Seedlings of these species were grown in polybags under each sludge treatment.

Soil samples were analyzed before and after the experiment to assess changes in fertility parameters. Soil organic carbon was determined by the Walkley and Black rapid titration method [28]. Available phosphorus in soil was determined by the Olsen's ascorbic acid method [57]. Available potassium was extracted using neutral ammonium acetate (pH 7.0) and measured with a flame photometer [18]. Electrical conductivity of the soil was measured in a 1:2 soil-water extract [15], and soil pH was determined using a glass electrode in a 1:2 soil-water suspension ([15]). Dehydrogenase activity (DHA) in soil was assayed by the method of [27], which measures the reduction of triphenyl tetrazolium chloride (TTC) to triphenyl formazan (TPF). Micronutrients (Fe, Mn, Cu, Zn) in soil were extracted by the DTPA (diethylenetriamine pentaacetic acid) method as described by [17] and measured using an atomic absorption spectrophotometer (AAS).

After 12 months of growth, the seedlings were harvested. Plant dry matter of roots and shoots was determined. The total nitrogen in plant samples was measured by standard Kjeldahl digestion and distillation, and plant phosphorus and potassium contents were determined after acid digestion of plant material, using colorimetric and flame photometric methods, respectively. Micronutrient concentrations (Zn, Fe, Mn, Cu) in plant tissues were determined by digesting the dried plant samples and analyzing by AAS. Statistical analysis of the data was done using factorial CRD analysis with software developed by the Department of Mathematics, Statistics and Physics at Punjab Agricultural University, Ludhiana.

4. RESULTS AND DISCUSSION

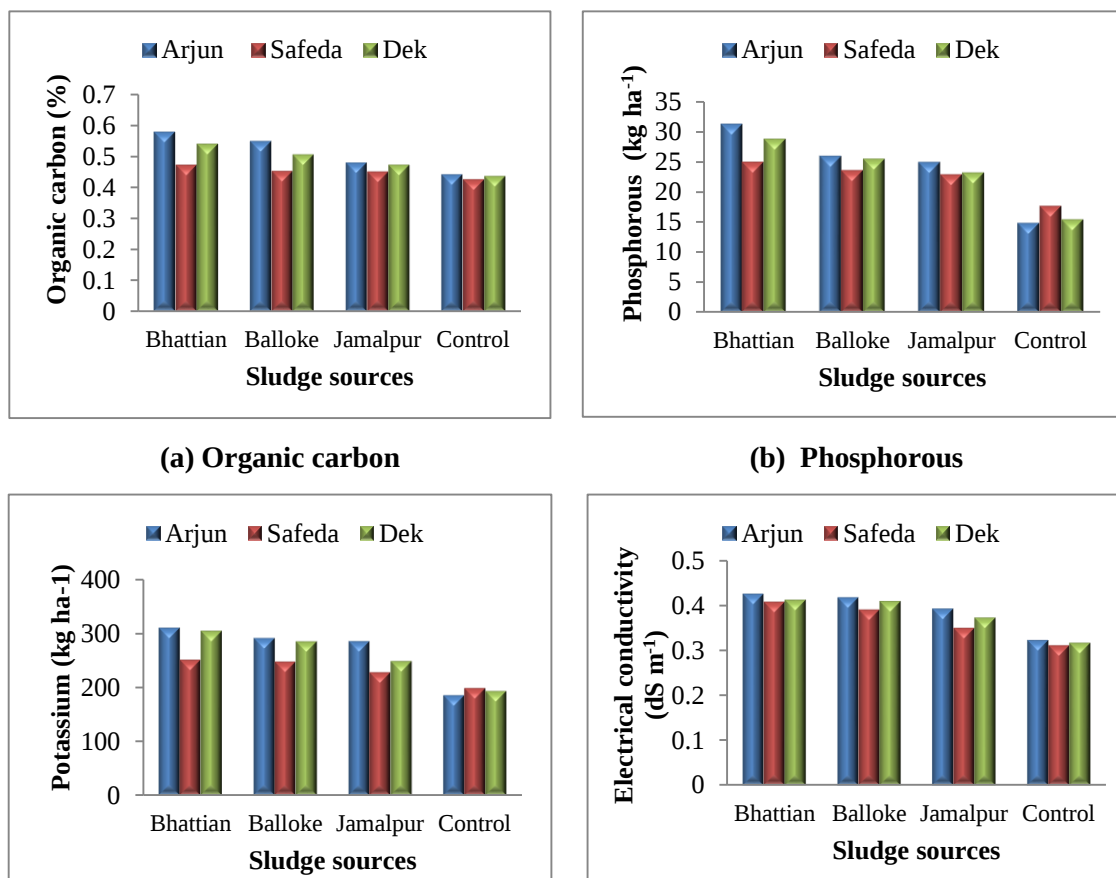
Sludge characteristics: Figure 1 shows the nutrient composition of the sludge used from the three treatment sites, compared to the control soil. The sludge contained substantial amounts of macronutrients (N, P, K) and micronutrients (Zn, Fe, Mn, Cu) that could potentially enhance soil fertility.



**Concentration of sludge was 1% of the total soil weight per polybag*

Fig. 1. Nutrient composition of the sludge used from the three treatment sites, compared to the control soil

Soil properties: The data presented in Figure 2 reveal the effect of sludge from various treatment plants on key soil quality parameters, namely organic carbon, phosphorus, potassium, electrical conductivity, pH, and dehydrogenase activity.



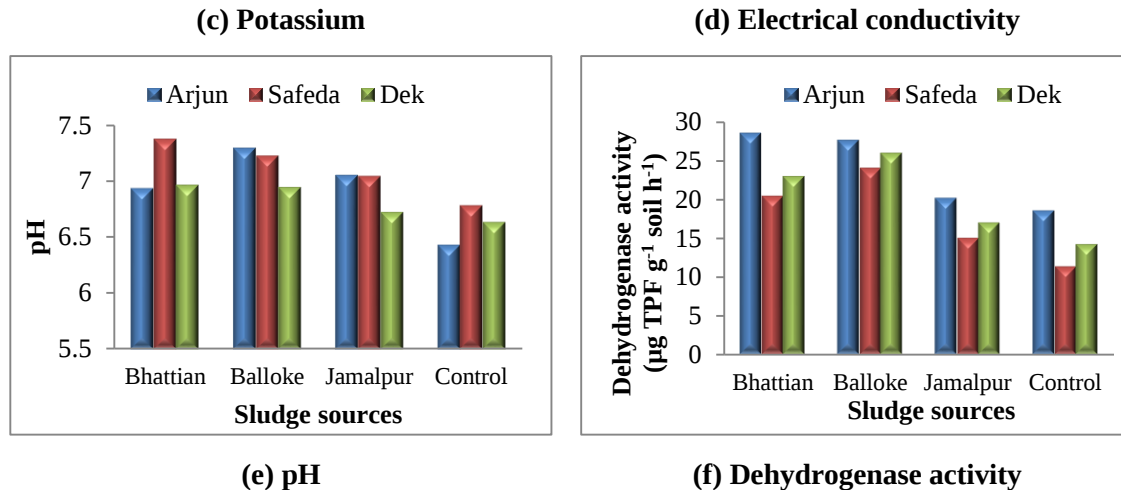


Fig. 2. Effect of sludge from various sources on soil parameters of three tree species.
Phosphorous (kg ha^{-1})

Organic carbon (%): Irrespective of plant species, soil treated with sludge from Bhattian had a mean organic carbon content of 0.53%. This was at par with soil treated with sludge from Balloke (0.50%), but significantly higher than that in soil treated with sludge from Jamalpur (0.47%) or the control (0.43%). Conversely, irrespective of sludge source, the mean soil organic carbon under Arjun (0.51%) and Dek (0.48%) did not differ significantly, but the value under Safeda (0.45%) was significantly lower than in Arjun and Dek. The initial organic carbon content before the experiment was 0.21%. Thus, application of sludge led to a substantial increase in soil organic carbon. Increasing evidence indicates that sewage sludge compost incorporated into soil raises soil organic carbon levels [6]. [32] found that sludge addition improved topsoil fertility, with total organic carbon increasing in a dose-dependent manner. [40] also reported that applying sewage sludge compost results in a significant increase in organic soil carbon.

Phosphorus (kg ha^{-1}): The available phosphorus content in the initial soil sample was 14.3 kg ha^{-1} . Irrespective of plant species, the mean available phosphorus was highest in soil treated with sludge from Bhattian (28.4 kg ha^{-1}), followed by Balloke (25.1 kg ha^{-1}) and Jamalpur (23.7 kg ha^{-1}), with the lowest in the control (16.0 kg ha^{-1}). Irrespective of sludge treatment, the mean soil phosphorus in Arjun (24.3 kg ha^{-1}) was significantly higher than in Dek (23.3 kg ha^{-1}) or Safeda (22.3 kg ha^{-1}). The values for Dek and Safeda were at par with each other but significantly lower than for Arjun. Increasing evidence shows that sewage sludge compost increases nutrient content in soil, including phosphorus ([6]). [32] reported that sludge addition improved soil P, with a significant dose-dependent increase in available P. [56] likewise found that sewage sludge application significantly increased soil phosphorus concentrations by 22–54%.

Potassium (kg ha^{-1}): The available potassium content in the initial soil was 173.6 kg ha^{-1} . After sludge treatments, irrespective of species, the mean available K in soil treated with Bhattian sludge was 288.2 kg ha^{-1} , which was significantly higher than that in soil treated with Balloke (274.3 kg ha^{-1}) or Jamalpur sludge (253.8 kg ha^{-1}). All sludge-treated soils had much higher K than the control (192.1 kg ha^{-1}). Similarly, among species, the mean soil K under Arjun (268.0 kg ha^{-1}) was significantly higher than under Dek (257.3 kg ha^{-1}) or Safeda (231.0 kg ha^{-1}). [56] observed that sewage sludge application increased soil K by 23–27%. [38] also reported that soluble potassium increased in sandy and calcareous soil with higher rates of sewage sludge application.

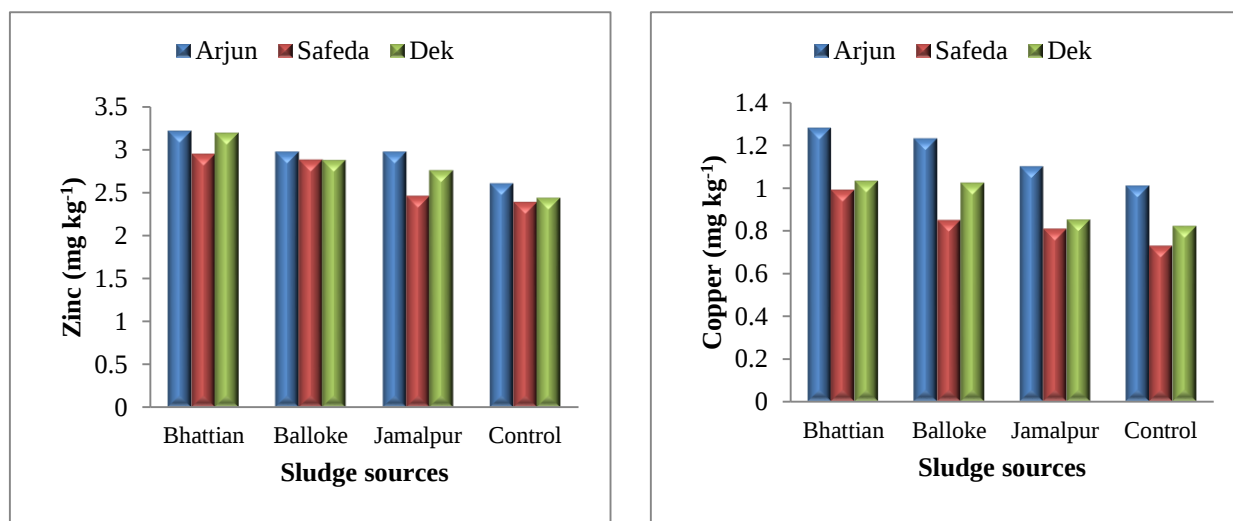
Electrical conductivity (dS m^{-1}): Soil electrical conductivity (EC) in sludge-treated samples did not differ

significantly among the different sludge sources; all sludge-amended soils had similar EC values. However, the sludge-treated soil collectively showed higher EC than the control soil (which had EC 0.320 dS m^{-1}). The initial soil EC was 0.324 dS m^{-1} . [38] reported that increased soil EC because of sludge application may be attributed to the high salt content of sewage sludge. This agrees with findings of [35], [36], [33], and [37], all of whom observed that soil EC rises with sewage sludge application. On the other hand, [39] found that the EC of chemically fertilized soil was higher than that of soils under sewage sludge treatments, indicating that the effect on EC can depend on the type of amendment.

pH: Soil pH showed no significant variation among any of the sludge treatments or tree species – pH values were at par across all sludge-treated samples. In other words, sludge application did not markedly affect soil pH in this experiment. [56] found that sewage sludge application did not significantly change soil pH. Some studies have noted that sludge compost can help buffer soil pH by improving moisture retention and aeration [7], [20]. In some cases, researchers observed slight pH increases (0.5–1.6 units) after sludge compost application [9], while others reported pH decreases under heavy sludge loading [33], [34]. These differences suggest that sludge effects on soil pH can vary depending on soil type and sludge application rate.

Dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$): Dehydrogenase enzyme activity in soil increased markedly with sludge application. Irrespective of tree species, soil treated with Bhattian sludge had the highest DHA ($24.0 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$), followed by soil with Balloke sludge (23.7) and Jamalpur sludge (17.4), compared to the control soil (14.6). The initial DHA before treatments was only $3.2 \mu\text{g TPF g}^{-1} \text{ soil h}^{-1}$, indicating that all treatments, especially Bhattian, greatly stimulated microbial activity. Irrespective of sludge source, the mean soil DHA under Arjun (23.7) was significantly higher than under Dek (20.1) or Safeda (17.1). The enhanced dehydrogenase activity is likely due to the higher organic carbon in sludge-treated soils, which supports greater microbial populations and activity. [46] observed a 102% increase in soil DHA at a sewage sludge application rate of 5 t/da , attributing it to the high organic matter in sludge boosting microbial biomass. [45] also found a strong positive correlation between soil organic C and dehydrogenase enzyme activity. Our findings align with these reports, confirming that organic amendments like sludge can significantly enhance soil biological activity.

Soil micronutrients: Figure 3 shows the effect of sludge application on available micronutrient levels (zinc, copper, iron, and manganese) across the three species. In general, sludge-treated soils had higher micronutrient availability than the control, although differences among the sludge sources were relatively small.



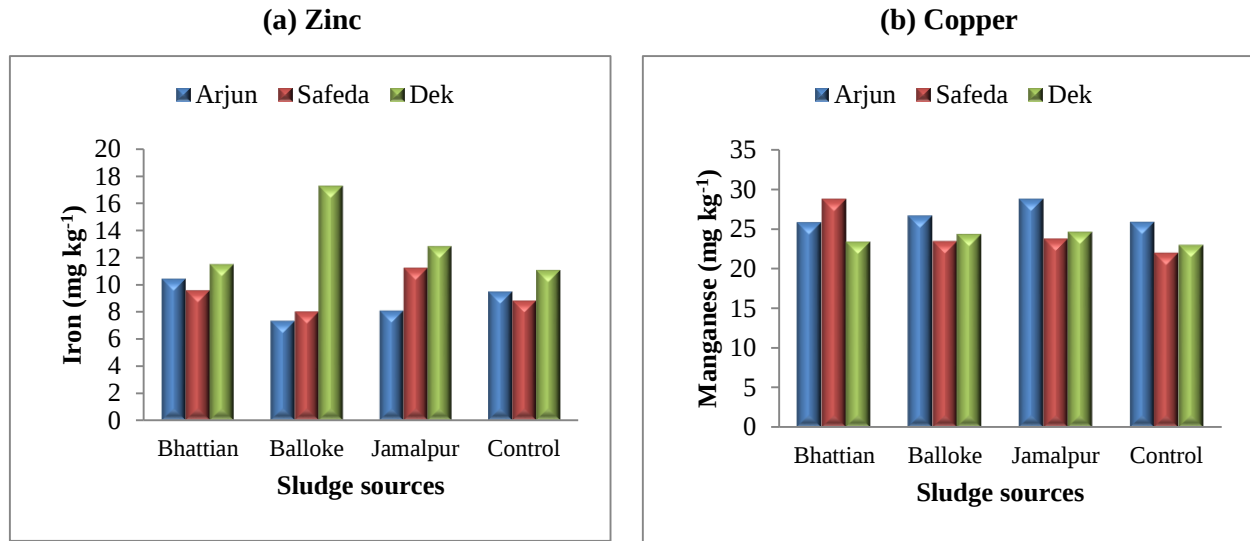
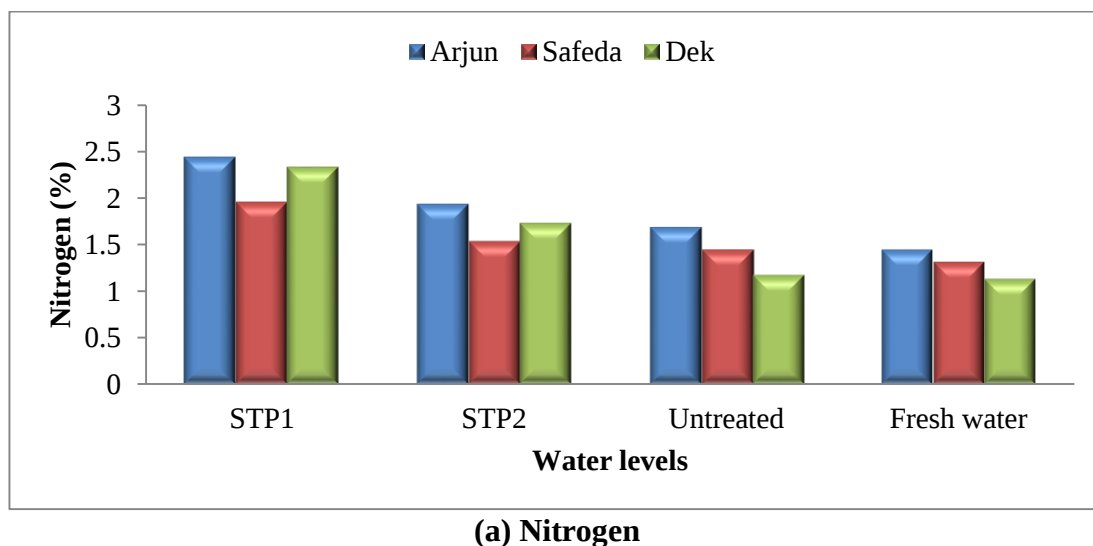
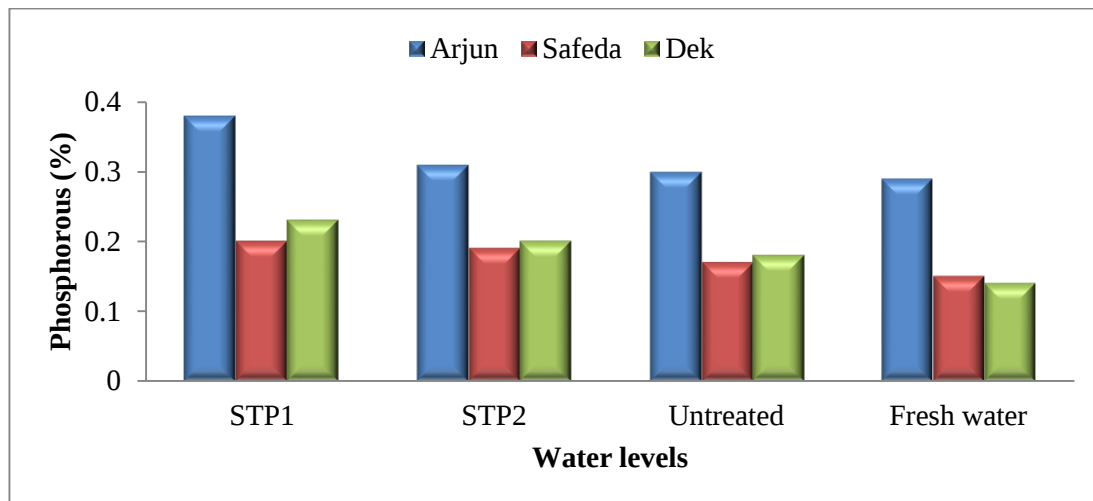


Fig. 3. Effect of sludge from various sources on soil micronutrients of three tree species.

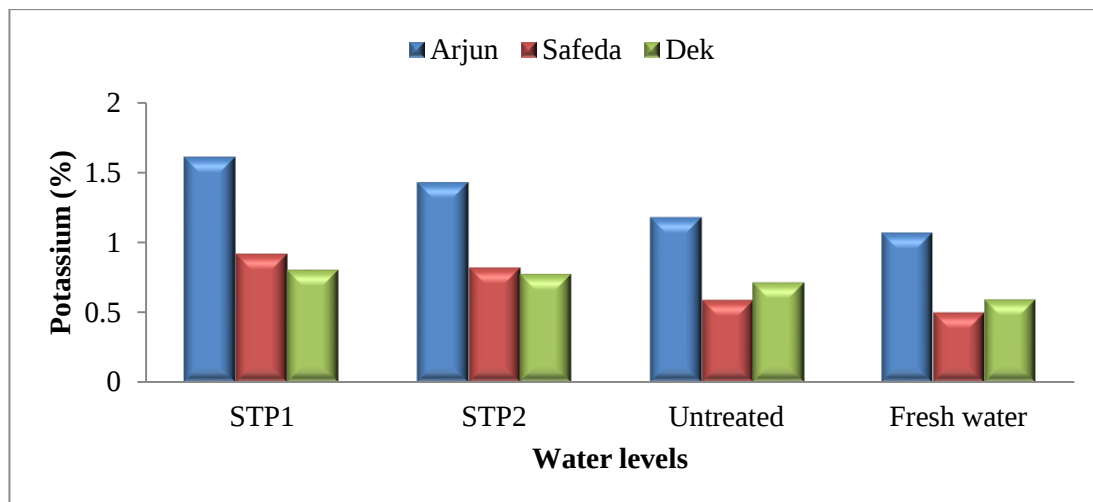
The sludge amendments tended to increase soil Zn, Cu, Fe, and Mn concentrations compared to the control, but in our study these differences were not statistically significant among the different sludge sources. There were also no significant differences among tree species in soil Zn or Fe levels under the sludge treatments. This suggests that the sludge effect on soil micronutrients was broadly similar regardless of tree species or sludge origin. Nevertheless, the overall improvement in micronutrient availability with sludge is noteworthy. For example, [13] reported that the zinc content of a sludge-amended soil reached 762 mg L⁻¹, compared to only 37 mg L⁻¹ in unamended control, illustrating the potential of sludge to supply micronutrients. In our experiment, all sludge-treated soils had soil Zn, Cu, Fe, and Mn levels numerically higher than the control (Figure 3), indicating that even though between-treatment differences were small, the sludge did enrich the soil micronutrient pool available to plants.

Plant macronutrients: Figure 4 depicts the effect of sludge from the three locations on plant macro-nutrient contents – nitrogen, phosphorus, and potassium – in the seedlings' shoots and roots.





(b) Phosphorus



(c) Potassium

Fig. 4. Effect of sludge from various sources on plant macronutrients of three tree species.

Nitrogen (%): In all three species, the nitrogen content was higher in shoots than in roots. Arjun exhibited the highest nitrogen levels among the species. The Arjun seedlings had a shoot nitrogen content of 2.69% with Bhattian sludge, followed by 2.33% with Balloke sludge and 2.21% with Jamalpur sludge, all significantly higher than the control (1.57%). In Safeda, the maximum shoot N was 1.50% (Bhattian), followed by 1.31% (Balloke) and 1.11% (Jamalpur), again all higher than the control (0.82%). Dek showed a similar trend, with shoot N reaching 1.64% (Bhattian) versus 1.34% and 1.23% with the other sludge treatments, compared to 0.82% in the control. Thus, sludge applications substantially increased plant nitrogen uptake, with Bhattian sludge having the strongest effect. [9] likewise found that *Mangifera persiciforma* plants treated with sewage sludge compost had higher nitrogen levels in their tissues (up to 11.98 g/kg dry weight) – a change that positively affected plant growth. [5] also reported that grain N content in barley increased with the addition of sludge to soil, reflecting improved N nutrition.

Phosphorus (%): Sludge application also enhanced plant phosphorus content. Arjun shoots had the highest phosphorus concentration at 0.54% with Bhattian sludge, compared to 0.26% and 0.25% with Balloke and Jamalpur sludge, respectively, all above the control (0.23%). In Safeda, the shoot P reached 0.18% with Bhattian sludge versus 0.16% and 0.15% with the other sludge sources (control 0.14%). Dek shoots showed

a maximum of 0.21% P (Bhattian) compared to 0.20% and 0.18% (control 0.15%). Among the species, Arjun accumulated the most phosphorus overall. These results indicate that sludge amendments improved P uptake in all species, with the largest gains observed with Bhattian sludge. Whitman et al. (2016) observed increased P content in plant tissues resulting from sludge application, attributing it to the retention of phosphorus by the organic matter in sludge.

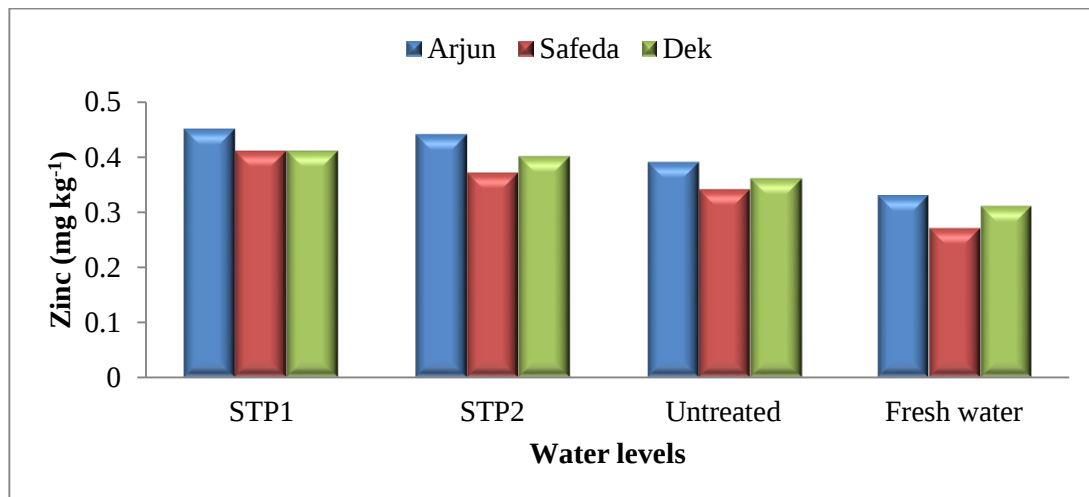
Potassium (%): Plant potassium content followed a similar pattern. Arjun shoots had the highest K, at 1.73% with Bhattian sludge, versus 1.46% and 1.22% with Balloke and Jamalpur sludge (control plants had 1.15%). In Safeda, shoot K reached 0.74% with Bhattian, 0.70% with Balloke, and 0.56% with Jamalpur (control 0.46%). Dek shoots had a maximum of 1.09% K with Bhattian sludge, about the same (1.08%) with Balloke, and 0.85% with Jamalpur (control 0.58%). Overall, Arjun accumulated more K than the other species under all treatments. These findings demonstrate that sludge (particularly from Bhattian) improved potassium nutrition in the seedlings. [9] similarly reported that sewage sludge compost increased potassium levels in plant tissues (up to 10.16 g/kg dry weight in their study), which had a positive effect on plant growth.

The above results for N, P, and K indicate that sludge amendments significantly enhanced the macronutrient status of the tree seedlings. Among the sludge sources, Bhattian sludge was most effective, and among the species, Arjun showed the greatest uptake of nutrients, followed by Dek and Safeda. Previous studies have noted that sludge with higher nutrient content can lead to better growth and nutrient accumulation in plants [21]. Our findings are consistent with the expectation that organic waste like sewage sludge can serve as a valuable fertilizer, improving the nutritional quality of planting stock in nurseries.

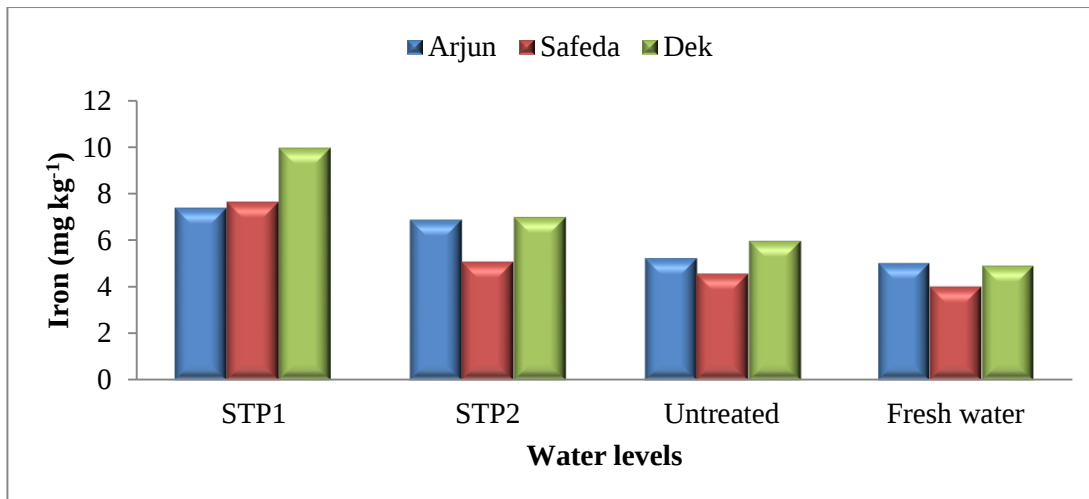
Plant micronutrients: Figure 5 illustrates the effect of the sludge treatments on the total micronutrient content (zinc, iron, and manganese) in the plant tissues (combined root and shoot) of the three species.

Zinc (mg kg⁻¹): Sludge application significantly increased zinc uptake in all species. Arjun seedlings had the highest total Zn, reaching 0.54 mg kg⁻¹ (dry weight) with Bhattian sludge, compared to 0.40 and 0.38 with Balloke and Jamalpur, respectively (control plants contained 0.33 mg kg⁻¹ Zn). In Safeda, the maximum Zn was 0.33 mg kg⁻¹ (Bhattian) vs. 0.32 and 0.29 (control 0.24). Dek had a maximum of 0.39 mg kg⁻¹ Zn (Bhattian) vs. 0.36 and 0.33 (control 0.28). Thus, Bhattian sludge led to the highest Zn accumulation, and Arjun accumulated more Zn than Safeda or Dek under all treatments. Across species, Arjun's overall mean Zn content was 0.41 mg kg⁻¹, higher than Dek (0.34) and Safeda (0.29). The enhanced zinc in sludge-treated plants is directly related to the sludge's zinc content. [4] also recorded increased Zn (and other micronutrients) in plants grown in sludge-amended soil. [9] found that sludge applications increased zinc availability in soil, which likely explains the greater Zn uptake observed in our sludge-treated seedlings.

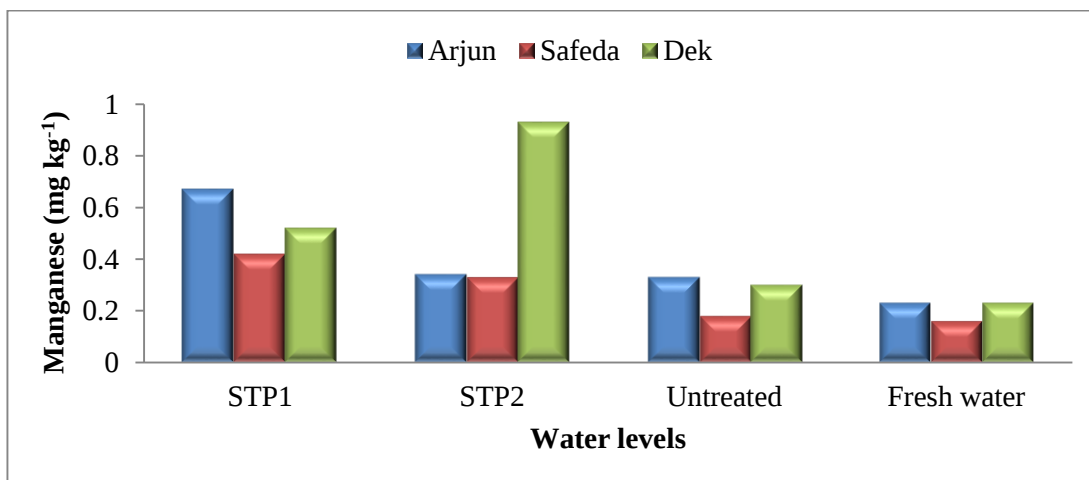
Iron (mg kg⁻¹): Plant iron content was also improved by sludge. Arjun again showed the highest values, with iron reaching 7.55 mg kg⁻¹ under Bhattian sludge, compared to 6.93 and 5.39 with Balloke and Jamalpur (control 4.24). Safeda's highest Fe was 4.58 mg kg⁻¹ (Bhattian) vs. 4.30 and 3.62 (control 3.05). Dek had 7.11 mg kg⁻¹ Fe (Bhattian) vs. 6.27 and 4.63 (control 4.12). These results show that Bhattian sludge led to the greatest Fe uptake, and Arjun and Dek accumulated more Fe than Safeda. Wang et al. (2018) reported that sewage sludge can increase iron content in plants due to the formation of metal–organic complexes, which enhance micronutrient availability. Our observations align with this, as sludge-treated plants (especially with Bhattian sludge) had considerably higher iron than the untreated controls.



(a) Zinc



(b) Iron



(c) Manganese

Fig. 5. Effect of sludge from various sources on plant micronutrients of three tree species.

Manganese (mg kg⁻¹): A similar trend was observed for manganese. Arjun seedlings had the highest Mn content, at 0.47 mg kg⁻¹ with Bhattian sludge, compared to 0.39 and 0.31 with Balloke and Jamalpur (control

0.17). In Safeda, the maximum Mn was 0.34 mg kg⁻¹ (Bhattian) vs. 0.31 and 0.27 (control 0.21). Dek's maximum Mn was 0.34 (Bhattian) vs. 0.32 and 0.29 (control 0.16). Overall, Arjun > Dek > Safeda in manganese accumulation, and Bhattian sludge had the strongest effect among sludge types. The fact that sludge-treated plants show higher Mn than control is consistent with other studies. [9] concluded that *M. persiciforma* plants treated with sewage sludge compost had increased Mn in their tissues and enhanced Mn uptake, which positively affected plant growth. Our findings similarly highlight that sludge amendments can boost plant Mn levels, although differences between sludge sources were modest.

In summary, the use of municipal sludge as a soil amendment significantly improved the fertility status of the soil and the nutritional quality of tree seedlings in the nursery. Sludge from the Bhattian treatment plant, which had relatively higher nutrient content (Figure 1), was the most effective in enhancing soil nutrients and plant nutrient uptake, followed by sludge from Balloke and Jamalpur. Among the tree species, *Terminalia arjuna* (Arjun) consistently showed the highest uptake of both macro- and micro-nutrients, indicating a strong growth response to sludge fertilization. *Melia composita* (Dek) also responded well, while *Eucalyptus* clone 413 (Safeda) showed comparatively lower nutrient uptake under the same conditions. These differences could be due to inherent species traits in nutrient absorption and growth rates. Nevertheless, all three species benefited from sludge application, showing improved nutrient status relative to the control.

Using sewage sludge in nursery potting mix appears to be a viable way to recycle waste while enhancing plant growth. However, it is important to monitor soil parameters such as salinity (EC) and ensure that heavy metals remain within safe limits. In our study, sludge applications did not adversely affect soil pH and only slightly increased EC, staying within acceptable ranges. The substantial increases in soil organic carbon and microbial activity (DHA) suggest improved soil health and fertility with sludge. The overall positive outcomes indicate that municipal sludge, when properly processed and applied at appropriate rates, can serve as a valuable organic fertilizer in forest nurseries, contributing to sustainable waste management and forestry practices.

5. CONCLUSION

The results of this study demonstrate that the application of municipal sewage sludge significantly improves soil fertility and enhances the nutritional status of tree species cultivated under nursery conditions. Among the sludge sources evaluated, sludge from the Bhattian sewage treatment plant yielded the most beneficial effects on soil macronutrients (phosphorus and potassium), organic carbon content, and biological indicators such as dehydrogenase activity. Notably, the Arjun (*Terminalia arjuna*) plants grown in sludge-treated soil exhibited the greatest enhancement in soil phosphorus, potassium, organic carbon, pH, and microbial activity compared to Dek (*Melia composita*) and Safeda (*Eucalyptus* clone 413), irrespective of the sludge treatment applied.

In addition to improving soil properties, sludge application positively influenced micronutrient dynamics. The Bhattian sludge treatment led to significantly higher concentrations of zinc, copper, and manganese in the soil, regardless of the tree species. Correspondingly, plant tissue analysis revealed enhanced accumulation of macronutrients (nitrogen, phosphorus, and potassium) in all tree species grown in sludge-amended soils, with Arjun again showing the highest uptake across all parameters. Arjun seedlings also contained the highest concentrations of micronutrients (zinc, iron, and manganese), followed by Dek and Safeda, indicating superior nutrient absorption capacity and growth performance.

These findings collectively confirm that the judicious use of treated municipal sludge can serve as an effective soil amendment in tree nurseries, improving both soil quality and plant nutrition without adverse impacts. Arjun emerged as the most responsive species in terms of nutrient uptake and soil enrichment, underscoring

its potential suitability for afforestation and land reclamation programs that incorporate organic waste recycling for sustainable soil fertility management.

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