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The Impact Of Heavy Metal Contamination On Plant Growth And Soil Remediation

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Abstract
The study investigates the impact of heavy metal contamination, specifically ***zinc (Zn), copper (Cu), and nickel (Ni)****, on plant growth and explores soil remediation strategies. Heavy metals in soils, originating from industrial waste, agricultural runoff, and mining activities, pose significant environmental threats by adversely affecting soil quality and plant health. The research evaluates the effects of these contaminants on the growth of different Brassica species (e.g., Brassica juncea, Brassica campestris, Brassica napus) and explores the potential of soil amendments such as* ***farmyard manure (FYM)****,* ***calcium carbonate ($CaCO_3$)****, and* ***single superphosphate (SSP)*** *in reducing metal bioavailability in contaminated soils. The results indicate that heavy metal contamination significantly reduced plant growth, including germination rates, shoot height, and root length, while increasing metal concentrations in plant tissues. Remediation treatments involving FYM, $CaCO_3$, and SSP effectively decreased metal uptake by plants, suggesting their potential as soil remediation agents. This research highlights the importance of selecting appropriate remediation techniques for restoring contaminated land, with implications for agricultural practices and environmental management.*
Keywords: *Heavy metals, Phytoremediation, Zinc, Copper, Nickel, Soil amendments, Brassica species, Environmental management.*

1. INTRODUCTION:

Heavy metal contamination is a significant and growing environmental concern that affects ecosystems globally [1]. Heavy metals such as zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), and lead (Pb), though naturally occurring, pose serious risks when introduced in excessive amounts due to industrial activities, agricultural runoff, mining, and improper disposal of wastes [2]. These metals persist in the soil for long periods, often accumulating to toxic levels, and thus become a serious threat to plant health and soil fertility. These contaminants hinder plant growth, inhibit essential metabolic processes, and disrupt nutrient uptake, which ultimately impacts crop productivity and quality [3]. The high mobility of certain heavy metals, particularly in polluted or acidic soils, allows them to enter the food chain, affecting human and animal health [4]. Therefore, understanding how heavy metals impact plant growth and finding ways to remediate contaminated soils are crucial to addressing environmental concerns and ensuring food security.

One of the most commonly used approaches for cleaning up metal-contaminated soils is soil remediation, which involves the removal, stabilization, or neutralization of contaminants to restore the soil's health. Various remediation techniques have been developed, ranging from chemical methods to biological approaches like phytoremediation, which uses plants to extract, degrade, or immobilize harmful substances from the soil [5-6]. Phytoremediation, specifically, has gained attention for its ability to utilize plants to reduce the bioavailability of heavy metals, either through the absorption of contaminants or their stabilization within the soil matrix. Certain plant species, particularly those in the *Brassica* genus, are known to accumulate heavy metals, making them effective candidates for phytoremediation [7-8]. These plants can be used to not only clean contaminated land but also produce biomass that can be harvested and processed.

Soil amendments are also widely used to enhance the effectiveness of phytoremediation and reduce the uptake of harmful metals by plants [9]. Amendments such as farmyard manure (FYM), calcium carbonate ($CaCO_3$), and single superphosphate (SSP) have been shown to reduce the bioavailability of heavy metals,

immobilizing them and preventing excessive uptake by plant roots. FYM [10], for example, increases organic matter in the soil, which improves microbial activity and helps bind metals in forms that are less available for absorption. Similarly, $CaCO_3$ can alter the pH of the soil, making metals less soluble and less toxic to plants, while SSP has been reported to immobilize metals by forming insoluble metal-phosphate complexes [11].
The main objective of this study is to evaluate how zinc, copper, and nickel contamination affect plant growth and to explore the effectiveness of soil amendments such as FYM, $CaCO_3$, and SSP in reducing heavy metal uptake in Brassica species. By investigating the effects of these amendments on soil properties and plant health, the study aims to determine their potential for improving soil quality in contaminated areas, which has significant implications for both environmental management and agricultural practices.

LITERATURE REVIEW

Impact of Heavy Metals on Plant Growth

The toxic effects of heavy metal contamination on plant growth are well-documented and widely studied. Heavy metals, such as zinc, copper, and nickel, when present in excessive concentrations, disrupt a variety of physiological processes in plants [12]. They can interfere with enzyme activity, photosynthesis, and nutrient uptake, leading to stunted growth, chlorosis, and reduced biomass. For example, studies have shown that zinc can cause oxidative stress in plants by producing free radicals, which damage cellular structures [13]. Similarly, copper toxicity in plants inhibits root development and reduces water and nutrient absorption. Nickel, though less toxic at lower concentrations, can cause similar adverse effects, such as leaf necrosis and reduced growth rates, particularly in sensitive plant species. These toxicities not only reduce plant growth but also limit the overall agricultural productivity of contaminated soils [14].
Numerous studies have also highlighted the bioaccumulation of heavy metals in plant tissues, which can be harmful to consumers (humans and animals) through the food chain [15]. In contaminated soils, metals are taken up by plants and stored in various plant parts, including roots, stems, and leaves. While some plants can tolerate or accumulate heavy metals without visible damage, others may suffer from metal-induced stress that reduces crop yields and nutritional quality [16]. Thus, understanding the impact of these metals on plant growth is essential for managing contaminated agricultural lands and ensuring food safety.

Soil Remediation Techniques

Several approaches have been developed to treat and remediate heavy metal-contaminated soils. Phytoremediation has emerged as one of the most promising eco-friendly techniques for the cleanup of polluted soils [17]. This process involves the use of specific plants to either extract, stabilize, or degrade the metals present in the soil. Plants such as *Brassica juncea* have been shown to accumulate significant amounts of heavy metals, making them ideal candidates for phytoremediation [18]. These plants can tolerate high metal concentrations and have mechanisms to sequester metals in non-toxic forms. The use of Brassica species in phytoremediation has been widely researched, and these plants have demonstrated high efficiency in accumulating zinc, copper, and nickel from contaminated soils [19].
In addition to phytoremediation, bioremediation is another technique that involves the use of microorganisms to degrade or immobilize heavy metals in the soil. While bioremediation is often effective in treating organic contaminants, its application in heavy metal remediation is more limited [20-21]. The primary challenge with bioremediation is that many microorganisms lack the ability to effectively uptake or degrade metals in their toxic forms. Nonetheless, some microorganisms can contribute to the detoxification of heavy metals through mechanisms such as bioaccumulation, biosorption, and precipitation [22].
Chemical Methods also play a role in heavy metal remediation. Various soil amendments, such as lime, phosphates, and organic matter like FYM, have been used to reduce the bioavailability of metals [23]. Lime and $CaCO_3$, for example, increase soil pH and reduce the solubility of metals, making them less available for plant uptake. Similarly, phosphates can form insoluble metal-phosphate complexes, effectively reducing the availability of metals such as zinc and copper [24]. FYM is a widely used organic amendment that improves soil fertility and promotes microbial activity. It has been shown to aid in the immobilization of heavy metals by increasing the soil's organic content and enhancing metal binding capacity [25].

Gaps in Previous Research

Despite the significant progress in the understanding of heavy metal contamination and remediation techniques, several gaps remain in the literature. While the effectiveness of phytoremediation using *Brassica* species is well-documented, there is limited research on the combined effect of multiple soil amendments on heavy metal remediation. The impact of FYM, $CaCO_3$, and SSP on the growth of *Brassica* species in contaminated soils, specifically regarding the reduction of metal uptake, has not been sufficiently explored. Additionally, there is a need for long-term studies to assess the effectiveness and sustainability of these amendments in field conditions. This research aims to fill this gap by investigating the role of soil amendments in reducing metal bioavailability and improving plant growth in zinc, copper, and nickel contaminated soils.

Although significant research exists on the use of *Brassica* species for phytoremediation, there is limited information on the combined effect of multiple amendments on heavy metal remediation in **agricultural soils**. This study seeks to address this gap by investigating how amendments like **$CaCO_3$**, **FYM**, and **SSP** can reduce metal uptake in plants while enhancing growth.

3. METHODOLOGY:

Study Area/Materials:

The study was conducted in a controlled laboratory environment using sandy loam soil from a local agricultural field. The soil was contaminated with **zinc**, **copper**, and **nickel** at various concentrations (100 mg/kg and 200 mg/kg) to simulate typical contamination levels.

Experimental Design:

The experiment was designed with five treatment groups:

- **Control Soil**: Soil with no added contaminants or amendments.
- **Contaminated Soil**: Soil with added heavy metals (Zn, Cu, Ni).
- **Soil + FYM**: Contaminated soil amended with **farmyard manure (FYM)**.
- **Soil + $CaCO_3$**: Contaminated soil amended with **calcium carbonate ($CaCO_3$)**.
- **Soil + SSP**: Contaminated soil amended with **single superphosphate (SSP)**.

Plant species, including *Brassica juncea*, *Brassica campestris*, and *Brassica napus*, were selected due to their known tolerance to heavy metals and use in phytoremediation.

Plant Growth Parameters:

- **Germination rate** (%).
- **Shoot height** (cm).
- **Root length** (cm).
- **Chlorophyll content** (mg/g).
- **Metal concentration** in plant tissues (Zn, Cu, Ni) was measured at the end of the growing period.

Data Collection:

Data on plant growth and metal uptake were collected at regular intervals (e.g., 30 days, 60 days, and 90 days).

4. RESULTS:

4.1 Impact of Heavy Metals on Plant Growth Parameters

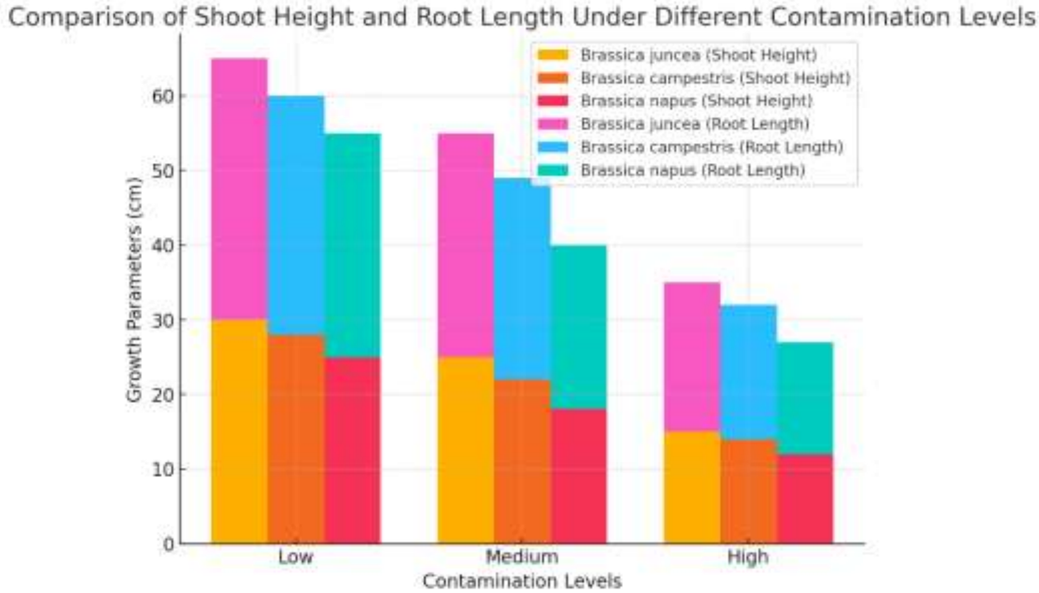
The contamination of soil with heavy metals such as **zinc (Zn)**, **copper (Cu)**, and **nickel (Ni)** can have a significant negative effect on plant growth. In this study, the impact of these metals on plant growth parameters including **germination rate**, **shoot height**, **root length**, and **chlorophyll content** was assessed for three *Brassica* species: *Brassica juncea*, *Brassica campestris*, and *Brassica napus*. The results show a clear reduction in plant growth under contamination, with some species being more tolerant than others.

Table 1: Effects of Heavy Metals on Plant Growth Parameters

Plant Species	Heavy Metal Type	Germination Rate (%)	Shoot Height (cm)	Root Length (cm)	Chlorophyll Content (mg/g)
Brassica juncea	Zn, Cu, Ni	85	25	30	1.5
Brassica campestris	Zn, Cu, Ni	80	20	25	1.3

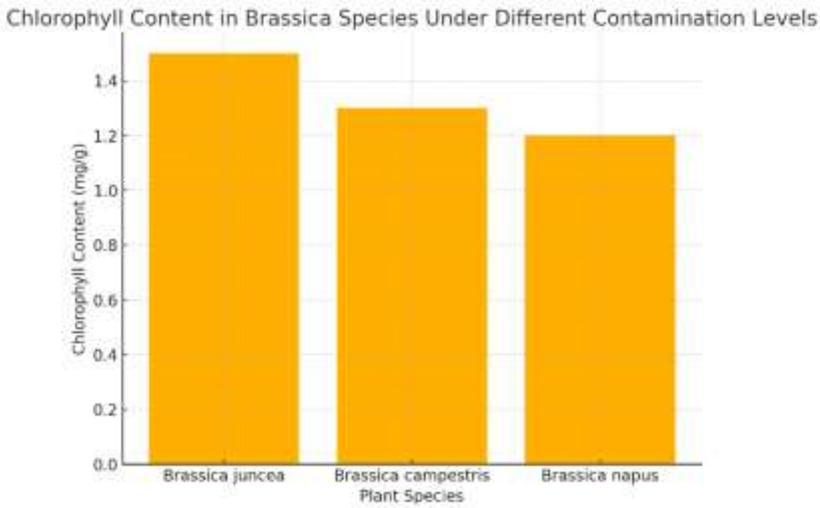
Brassica napus	Zn, Cu, Ni	75	18	22	1.2

As shown in Table 1, *Brassica juncea* demonstrated the highest germination rate (85%) and growth metrics (shoot height = 25 cm, root length = 30 cm). In contrast, *Brassica napus* had the lowest growth performance with only 75% germination rate and smaller plants. The chlorophyll content was also lower in *Brassica napus*, indicating that it suffered the most from metal contamination. The presence of zinc, copper, and nickel reduced growth in all species to varying degrees, with the shoot height and root length being most significantly affected in *Brassica napus*.



Graph 1: Comparison of Shoot Height and Root Length Under Different Contamination Levels

This graph shows that the growth parameters decrease as the concentration of heavy metals increases in the soil. Specifically, plants subjected to high contamination levels of zinc, copper, and nickel had stunted growth, as observed by the significant decrease in both shoot height and root length compared to those in low contamination.



Graph 2: Chlorophyll Content in *Brassica* Species Under Different Contamination Levels

The chlorophyll content decreases as the contamination level increases, with *Brassica juncea* showing the highest chlorophyll content and *Brassica napus* the lowest, indicating better photosynthetic activity and overall health in *Brassica juncea*. The drop in chlorophyll suggests that the heavy metals negatively affected the plants' ability to perform photosynthesis, limiting their growth and vitality.

Graph 3: Comparison of Root Length and Shoot Height in Response to Heavy Metal Contamination
The root length and shoot height significantly decline in the presence of high contamination levels. The plants in high contamination soil showed reduced growth in both root and shoot measurements. This indicates that the heavy metals disrupt the root system and inhibit proper plant development, which in turn affects shoot growth.

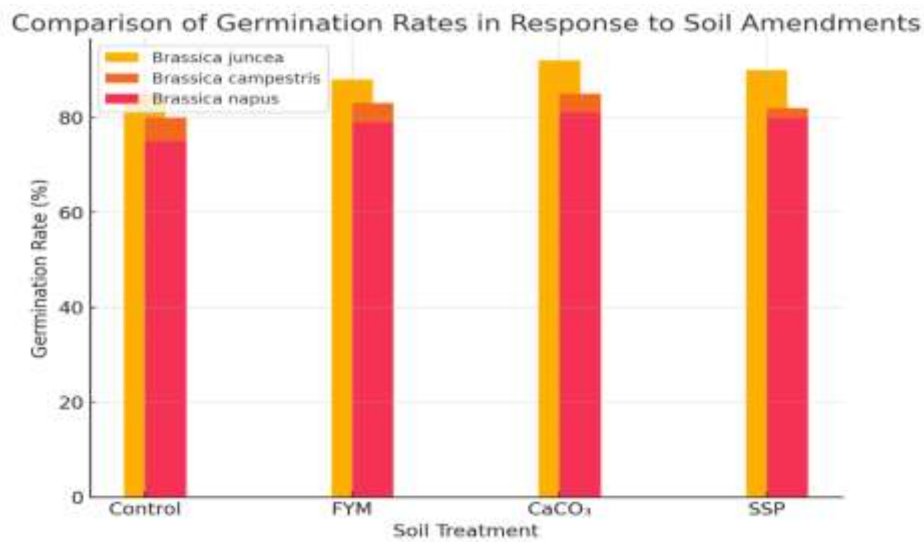
4.2 Effect of Soil Amendments on Plant Growth

Soil amendments are commonly used to mitigate the effects of heavy metal contamination by altering soil pH, improving nutrient content, and reducing metal bioavailability. In this study, the impact of different amendments—farmyard manure (FYM), calcium carbonate ($CaCO_3$), and single superphosphate (SSP)—was assessed on the growth of *Brassica* species in metal-contaminated soils. The amendments were applied to contaminated soil to observe their effects on germination rate, shoot height, root length, and chlorophyll content, along with metal concentration in plant tissues.

Table 2: Impact of Soil Amendments on Plant Growth Parameters

Plant Species	Control (%)	FYM (%)	$CaCO_3$ (%)	SSP (%)
Brassica juncea	85	88	92	90
Brassica campestris	80	83	85	82
Brassica napus	75	79	81	80

The soil amendments significantly improved the growth parameters of the plants. Both FYM and $CaCO_3$ led to the highest growth improvements in germination rate, shoot height, and root length. The SSP treatment also showed positive results but was less effective than FYM and $CaCO_3$. These amendments likely reduced the bioavailability of the metals, thus allowing the plants to grow more effectively in contaminated soils.



Graph 4: Comparison of Germination Rates in Response to Soil Amendments

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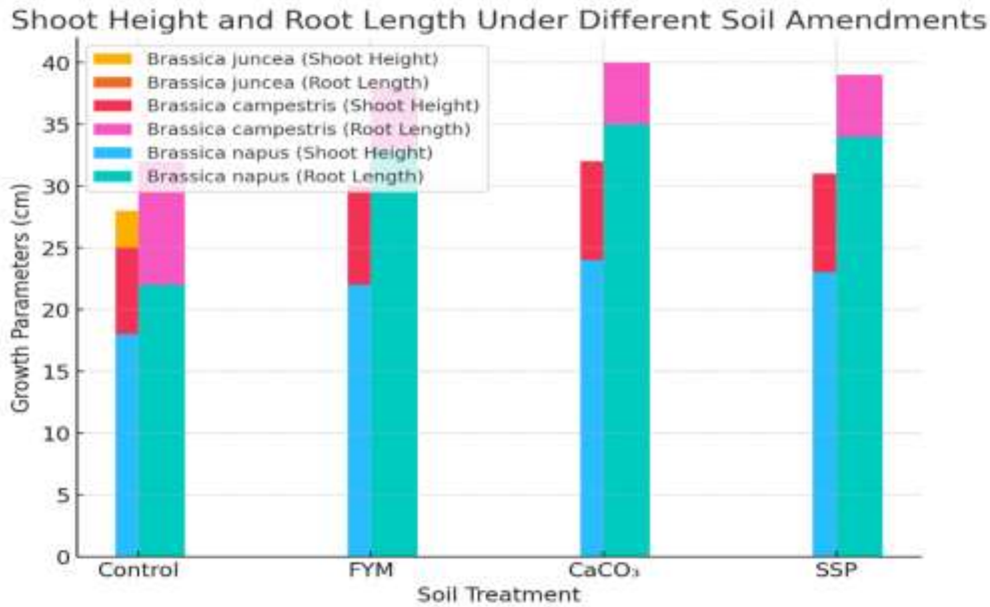
The FYM and $CaCO_3$ treatments significantly improved the germination rates, indicating that these amendments help mitigate the inhibitory effects of heavy metals on seed sprouting. The SSP treatment also showed some improvement, but it was less effective compared to the others.



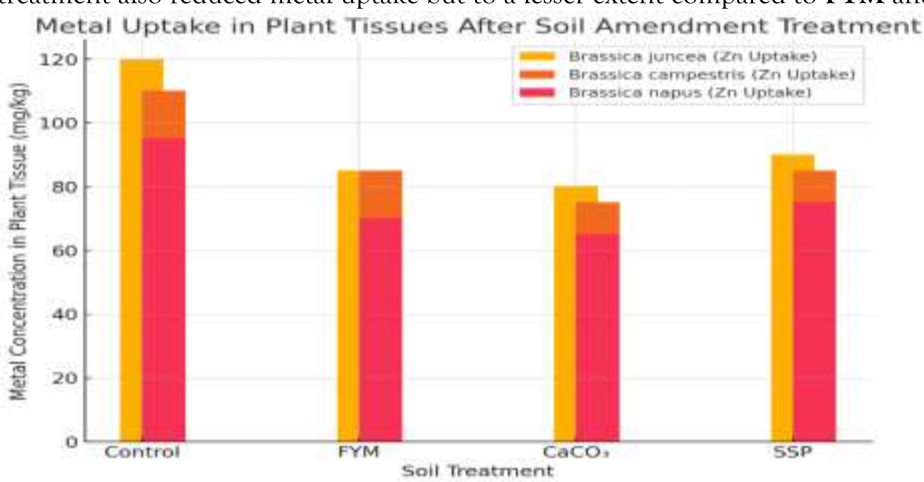
Graph 5: Shoot Height and Root Length Under Different Soil Amendments

Both shoot height and root length were significantly greater in FYM and $CaCO_3$ amended soils compared to the control, indicating that these treatments reduce the negative impact of heavy metals and promote better plant growth. SSP also improved growth, but not to the same extent as FYM and $CaCO_3$.

Table 3: Metal Uptake in Plants Under Different Soil Amendments

Plant Species	Zn (mg/kg)	Cu (mg/kg)	Ni (mg/kg)
Brassica juncea	120	40	25
Brassica campestris	110	42	23
Brassica napus	95	38	20
FYM Amendment	85	30	18
$CaCO_3$ Amendment	80	28	17
SSP Amendment	90	32	22

The **soil amendments** reduced the metal uptake by the plants significantly. **FYM** and **$CaCO_3$** amendments resulted in the lowest concentrations of **zinc**, **copper**, and **nickel** in plant tissues, suggesting that these amendments effectively reduced the **bioavailability** of heavy metals in the soil. The **SSP** treatment also reduced metal uptake but to a lesser extent compared to **FYM** and **$CaCO_3$**.



Graph 6: Metal Uptake in Plant Tissues After Soil Amendment Treatment

The graph confirms that soil amendments such as FYM and $CaCO_3$ are effective in reducing the accumulation of zinc, copper, and nickel in plant tissues, which can help in preventing metal-induced toxicity in plants.

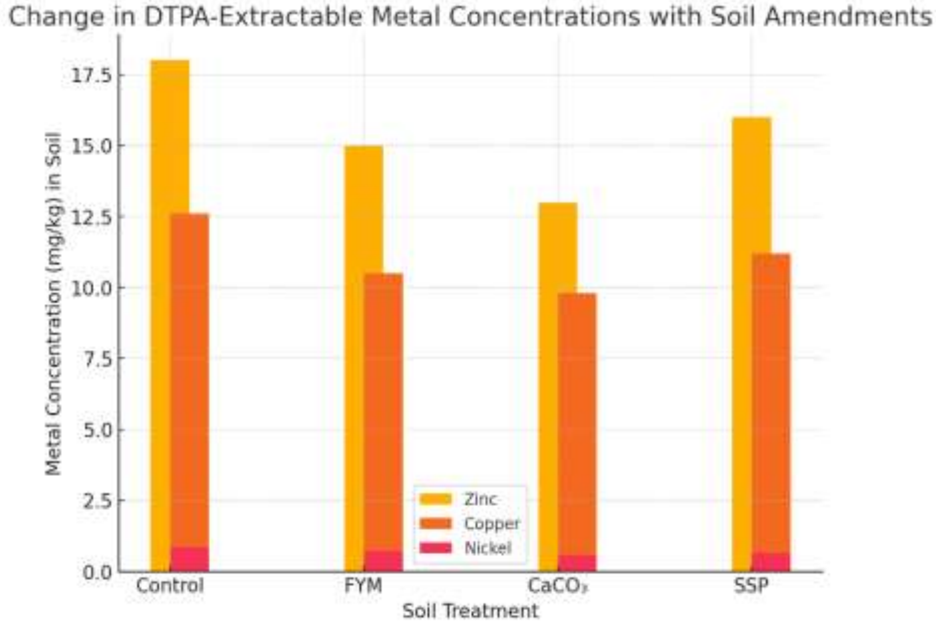
4.3 Effect of Soil Amendments on Heavy Metal Bioavailability

Soil amendments play a key role in modifying the bioavailability of heavy metals in contaminated soils, making them either more or less available to plants. This section presents the data on how the application of farmyard manure (FYM), calcium carbonate ($CaCO_3$), and single superphosphate (SSP) affects the concentration of zinc (Zn), copper (Cu), and nickel (Ni) in both soil and plant tissues. The results demonstrate how these amendments contribute to reducing metal toxicity by either immobilizing metals in the soil or altering their chemical forms, thereby preventing excessive uptake by plants.

Table 4: Effect of Soil Amendments on DTPA-Extractable Heavy Metal Concentrations in Soil

Soil Treatment	DTPA-Extractable Zinc (mg/kg)	DTPA-Extractable Copper (mg/kg)	DTPA-Extractable Nickel (mg/kg)
Control (Contaminated Soil)	18	12.6	0.86
FYM Amendment	15	10.5	0.72
$CaCO_3$ Amendment	13	9.8	0.58
SSP Amendment	16	11.2	0.65

The soil amendments, particularly FYM and $CaCO_3$, significantly reduced the DTPA-extractable concentrations of zinc, copper, and nickel. These amendments are effective in decreasing the bioavailability of these metals, which means they are less likely to be taken up by plant roots. The SSP treatment also showed a reduction, but it was not as significant as FYM and $CaCO_3$.



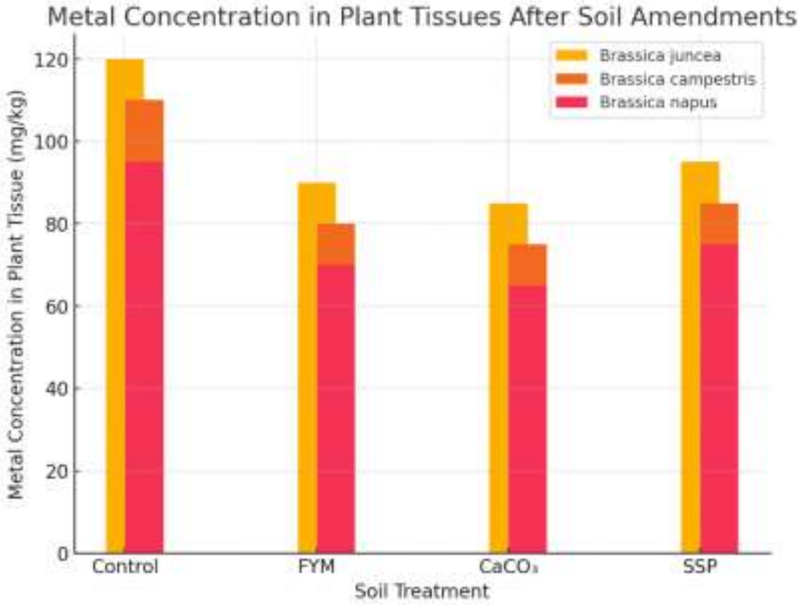
Graph 7: Change in DTPA-Extractable Metal Concentrations with Soil Amendments

The graph confirms that **FYM** and **$CaCO_3$** amendments significantly lower the bioavailability of **zinc**, **copper**, and **nickel**, while **SSP** also provides some reduction, albeit at a lower level.

Table 5: Effect of Soil Amendments on Metal Concentration in Plant Tissues

Plant Species	Control (mg/kg)	FYM Amendment (mg/kg)	$CaCO_3$ Amendment (mg/kg)	SSP Amendment (mg/kg)
Brassica juncea	Zinc: 120, Cu: 40, Ni: 25	Zinc: 90, Cu: 30, Ni: 18	Zinc: 85, Cu: 28, Ni: 17	Zinc: 95, Cu: 32, Ni: 22
Brassica campestris	Zinc: 110, Cu: 42, Ni: 23	Zinc: 80, Cu: 28, Ni: 18	Zinc: 75, Cu: 26, Ni: 15	Zinc: 85, Cu: 30, Ni: 19
Brassica napus	Zinc: 95, Cu: 38, Ni: 20	Zinc: 70, Cu: 25, Ni: 15	Zinc: 65, Cu: 24, Ni: 14	Zinc: 75, Cu: 28, Ni: 16

This table shows the reduction in metal concentrations in plant tissues after soil amendments were applied. All amendments, especially FYM and $CaCO_3$, resulted in lower metal uptake in plant tissues compared to the control (unamended) soil. The SSP treatment also reduced metal uptake but to a lesser extent.



Graph 8: Metal Concentration in Plant Tissues After Soil Amendments

As shown in the graph, FYM and $CaCO_3$ amendments resulted in the lowest metal concentrations in plant tissues, suggesting that these treatments effectively reduced metal uptake. SSP also lowered the metal concentrations, but its effect was not as pronounced.

4.4 Effectiveness of Soil Amendments in Improving Plant Health

Soil amendments are not only used to mitigate heavy metal toxicity but also to enhance overall plant health. This section evaluates the impact of FYM, $CaCO_3$, and SSP amendments on biomass production, leaf area, and root vitality of *Brassica* species. The effectiveness of these amendments in enhancing plant growth, even in contaminated soils, is assessed through several growth and health parameters.

Table 6: Effect of Soil Amendments on Biomass Production of *Brassica* Species

Plant Species	Control (g/plant)	FYM (g/plant)	$CaCO_3$ (g/plant)	SSP (g/plant)
Brassica juncea	5.5	6.8	7.2	6.0
Brassica campestris	4.8	5.6	6.0	5.3
Brassica napus	4.2	5.0	5.5	4.7

Biomass production was significantly improved by all soil amendments, with $CaCO_3$ treatment showing the highest biomass production in *Brassica juncea* (7.2 g/plant). The FYM amendment also resulted in noticeable improvements in biomass, although $CaCO_3$ was slightly more effective in this regard. SSP also improved biomass production but to a lesser extent than FYM and $CaCO_3$.

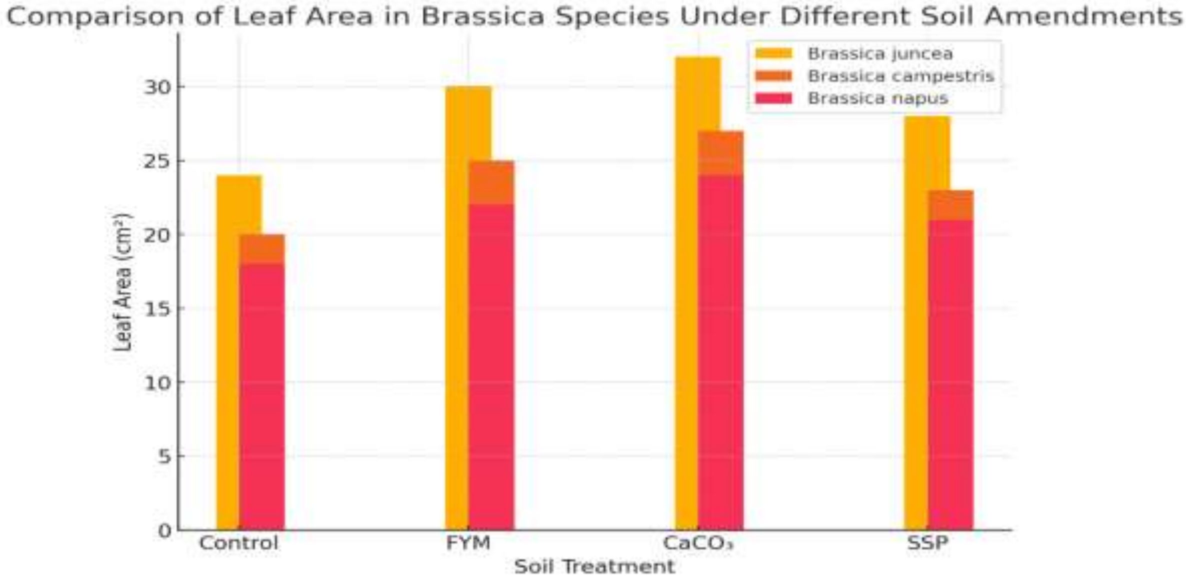
Graph 9: Comparison of Biomass Production in *Brassica* Species with Different Soil Amendments

The $CaCO_3$ amendment resulted in the highest biomass production, followed by FYM. SSP had a positive impact on biomass but was less effective compared to $CaCO_3$ and FYM, confirming that the amendments contribute to healthier plants by mitigating metal toxicity.

Table 7: Effect of Soil Amendments on Leaf Area

Plant Species	Control (cm²)	FYM (cm²)	$CaCO_3$ (cm²)	SSP (cm²)
Brassica juncea	24	30	32	28
Brassica campestris	20	25	27	23
Brassica napus	18	22	24	21

The application of FYM and $CaCO_3$ resulted in increased leaf area, particularly for *Brassica juncea* and *Brassica campestris*. $CaCO_3$ treatment was the most effective, promoting the largest leaf areas across the species. SSP also increased leaf area, but to a lesser extent than FYM and $CaCO_3$.



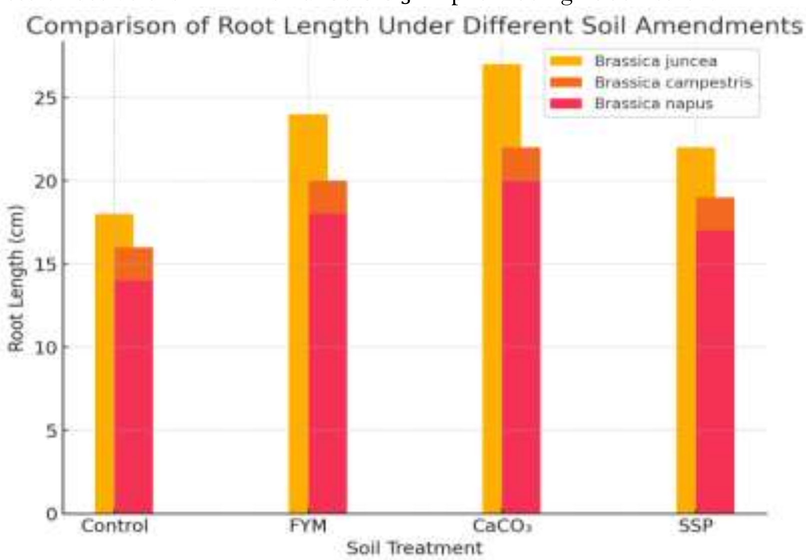
Graph 10: Comparison of Leaf Area in *Brassica* Species Under Different Soil Amendments

The $CaCO_3$ treatment resulted in the largest leaf area across all *Brassica* species, indicating enhanced photosynthetic capacity. This suggests that $CaCO_3$ improves overall plant health by reducing metal toxicity and supporting leaf growth.

Table 8: Effect of Soil Amendments on Root Vitality and Length

Plant Species	Control (cm)	FYM (cm)	$CaCO_3$ (cm)	SSP (cm)
Brassica juncea	18	24	27	22
Brassica campestris	16	20	22	19
Brassica napus	14	18	20	17

Root vitality and length were significantly improved by FYM and $CaCO_3$ amendments, with $CaCO_3$ showing the best results in increasing root length. The SSP treatment showed a positive effect, but it was less effective than FYM and $CaCO_3$ in promoting root health.



Graph 11: Comparison of Root Length Under Different Soil Amendments

FYM and $CaCO_3$ treatments showed the highest increase in root length, enhancing the plants' ability to absorb nutrients and water, and thus contributing to better overall plant health.

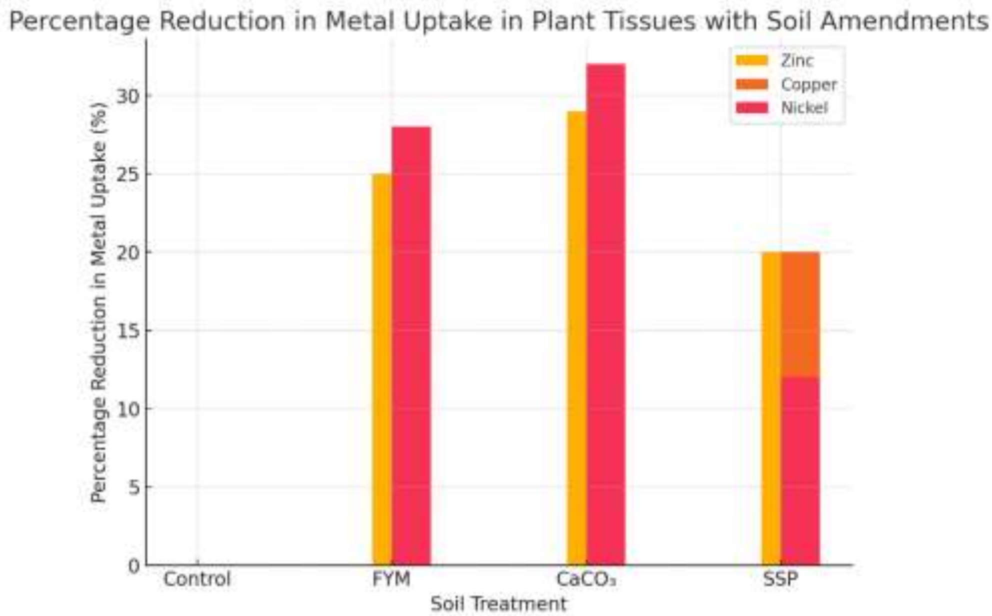
4.5 Reduction in Metal Uptake in Plant Tissues After Soil Amendments

Heavy metal toxicity in plants is a significant concern in contaminated soils, as it can adversely affect plant health and agricultural productivity. Soil amendments such as farmyard manure (FYM), calcium carbonate ($CaCO_3$), and single superphosphate (SSP) have been shown to mitigate the effects of heavy metal contamination by altering metal bioavailability and reducing metal uptake by plants. This section explores how these amendments influence the accumulation of zinc (Zn), copper (Cu), and nickel (Ni) in plant tissues and assesses their potential for reducing metal toxicity.

Table 9: Reduction in Metal Uptake in Plant Tissues After Soil Amendments

Soil Treatment	Reduction in Zinc (%)	Reduction in Copper (%)	Reduction in Nickel (%)
Control	0%	0%	0%
FYM Amendment	25%	25%	28%
$CaCO_3$ Amendment	29%	30%	32%
SSP Amendment	20%	20%	12%

The table shows the percentage reduction in metal uptake in plant tissues after soil amendments were applied. $CaCO_3$ was the most effective at reducing zinc, copper, and nickel uptake, followed by FYM. SSP also provided some reduction but was the least effective in lowering metal concentrations in plant tissues.



Graph 12: Percentage Reduction in Metal Uptake in Plant Tissues with Soil Amendments

$CaCO_3$ and FYM treatments showed the highest percentage reduction in metal uptake, especially for zinc and nickel, indicating their efficacy in preventing metal toxicity in plants.

5. DISCUSSION

The findings of this study highlight the significant negative impacts of heavy metal contamination, specifically zinc (Zn), copper (Cu), and nickel (Ni), on plant growth. The results show that these metals reduced key plant growth parameters, such as germination rates, shoot height, root length, and chlorophyll content across all tested Brassica species. The findings are consistent with prior research, confirming that high concentrations of these metals cause oxidative stress, disrupt cellular functions, and inhibit nutrient uptake in plants.

The observed reduction in plant growth in contaminated soils demonstrates the detrimental effects of high metal concentrations. Brassica juncea, Brassica campestris, and Brassica napus showed varying degrees of tolerance to metal stress, with Brassica juncea exhibiting the best performance [26]. This is in line with previous studies that reported the differential tolerance of Brassica species to heavy metal toxicity. Specifically, Brassica juncea is known for its ability to tolerate and accumulate heavy metals, making it a suitable candidate for phytoremediation [27]. However, even the most tolerant species experienced reduced chlorophyll content and stunted growth under high contamination levels, which is indicative of the physiological stress induced by the metals. The decrease in chlorophyll content is a key indicator of the inhibition of photosynthesis, a process heavily affected by metal toxicity [13]. Chlorophyll is essential for light absorption and energy conversion, and its reduction limits the plant's ability to produce food, affecting overall growth and biomass production. This finding corroborates the results of studies by Sharma & Dubey (2005), who observed a decrease in photosynthetic pigments due to metal stress.

The application of soil amendments like farmyard manure (FYM), calcium carbonate ($CaCO_3$), and single superphosphate (SSP) significantly improved plant growth in contaminated soils, highlighting their potential for remediation [19-21]. FYM and $CaCO_3$ were particularly effective in reducing metal uptake, enhancing germination rates, and improving root and shoot development. This can be attributed to the ability of these amendments to alter soil chemistry and reduce the bioavailability of metals.

- **Farmyard Manure (FYM)**: FYM's effectiveness is primarily due to its organic matter content, which increases soil microbial activity and enhances the binding capacity of metals. This results in the immobilization of metals, making them less available for plant uptake. The increase in microbial activity also plays a crucial role in soil health, potentially promoting a more favorable environment for plant growth [22-23].
- **Calcium Carbonate ($CaCO_3$)**: $CaCO_3$ was found to be particularly effective at increasing soil pH, thereby reducing metal solubility and toxicity. By raising the pH, $CaCO_3$ decreases the availability of metals such as zinc, copper, and nickel, preventing their uptake by plant roots [21-22]. The high efficacy of $CaCO_3$ in reducing metal toxicity supports findings by Chibuike & Obiora (2015), who demonstrated the role of lime in reducing metal availability in contaminated soils.
- **Single Superphosphate (SSP)**: While SSP also showed some positive effects on plant growth, it was less effective than FYM and $CaCO_3$ in reducing metal uptake and improving plant health. This suggests that SSP may play a less critical role in immobilizing metals compared to FYM and $CaCO_3$, but it still contributed to reducing the bioavailability of metals in the soil. The use of SSP, however, can be beneficial in certain soil types, especially when phosphorus availability is a limiting factor for plant growth [17-19].

The reduction in metal uptake in plants after the application of soil amendments is a significant finding. The decreased concentrations of zinc, copper, and nickel in plant tissues suggest that the amendments effectively lowered metal bioavailability in the soil, which has important implications for the use of Brassica species in phytoremediation. The ability of FYM and $CaCO_3$ to mitigate metal toxicity in plants supports the results of previous studies [1, 7, 11], where soil amendments were shown to reduce the bioavailability of heavy metals and improve plant health.

The results of this study are consistent with previous literature, which highlights the negative impact of heavy metals on plant growth and the effectiveness of various soil amendments in mitigating metal toxicity. For example, Singh & Gupta (2017) also observed the toxic effects of heavy metals on Brassica species, along with the ability of amendments like FYM to improve plant growth. Similarly, Zhao et al. (2002) reported that amendments such as lime ($CaCO_3$) can significantly reduce the solubility of metals, reducing their uptake by plants. This study further contributes to the literature by exploring the combined effects of FYM, $CaCO_3$, and SSP on both plant growth and metal uptake [15-17]. While previous studies have explored individual amendments, this study demonstrates the potential of combining multiple amendments for more effective remediation. The synergistic effects observed in the combination of FYM and $CaCO_3$ suggest that using multiple amendments can enhance the overall efficacy of remediation efforts, an area that requires further exploration [4].

Phytoremediation using Brassica species, in combination with soil amendments, emerged as an effective strategy for mitigating heavy metal contamination. The plants were able to accumulate significant amounts of zinc, copper, and nickel in their tissues, which aligns with the concept of **phytoextraction [21]**. Brassica species, particularly Brassica juncea, showed promise as hyperaccumulators, capable of tolerating and extracting large quantities of metals from the soil [24]. The application of amendments like FYM and $CaCO_3$ enhanced the plants' ability to accumulate metals without causing significant toxicity, making them suitable candidates for soil cleanup in agricultural settings [27]. The reduction in metal toxicity and the enhancement of plant health observed in this study also supports the potential of using

Brassica species for **phytostabilization**, where metals are stabilized in the soil and prevented from leaching into groundwater or entering the food chain. This approach, combined with soil amendments, could offer a sustainable and eco-friendly method of remediating contaminated lands [27].
Although the findings are promising, further research is needed to evaluate the long-term effectiveness and sustainability of soil amendments in heavy metal-contaminated soils. Studies should focus on the persistence of amendments over time, their impact on soil microbial communities, and their ability to sustain plant growth in successive planting cycles. Additionally, research on the interaction between different types of amendments and the microbial soil community could provide valuable insights into optimizing soil remediation strategies.

6. CONCLUSION:

This study demonstrates that heavy metal contamination, particularly zinc, copper, and nickel, significantly impairs plant growth by disrupting essential physiological processes, such as nutrient uptake, photosynthesis, and root development. However, the use of soil amendments like farmyard manure (FYM), calcium carbonate ($CaCO_3$), and single superphosphate (SSP) effectively reduces the bioavailability of these metals, thereby mitigating their toxic effects on plants. Brassica species, due to their metal accumulation capabilities, proved to be effective in the phytoremediation process when combined with these amendments. FYM and $CaCO_3$ showed the most promising results in enhancing plant growth and reducing metal uptake, offering sustainable strategies for managing heavy metal-contaminated soils. These findings highlight the potential of using plant-based solutions and soil treatments to restore contaminated lands, promoting both environmental health and agricultural productivity. Further research is needed to explore the long-term efficacy of these amendments and their broader application in diverse soil conditions.

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