Heavy Metal Contamination of Agroecosystem and Role of Plant Growth Promoting Microbe (PGPMs) in Bioremediation of Heavy Metals and Organophosphate Pesticide

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Agriculture production, food safety, and the environment are all seriously threatened by Pesticide and heavy metal contamination in agroecosystems. Typical sources of these pollutants are industrial activities, mining operations, inappropriate waste disposal, and the widespread application of chemical fertilizers and pesticides. Soil can accumulate heavy metals such as lead (Pb), cadmium (Cd), Chromium (Cr), and arsenic (As), which can then enter the food chain and cause severe health effects in both humans and livestock. Simultaneously, the widespread utilization of organophosphate insecticides, known for their severe toxicity to organisms, worsens the ecological imbalance and contributes to environmental contamination.

Bioremediation, which involves using the inherent capabilities of living organisms to cleanse contaminated environments, presents itself as a feasible and environmentally conscious solution to this predicament. Plant growth-promoting microorganisms (PGPMs) have attracted considerable interest for their potential in bioremediation among the many biological agents. Plant growth-promoting microorganisms (PGPMs), which include bacteria, fungi, and actinomycetes, promote plant development by many methods, such as nitrogen fixation, phosphate solubilization, synthesis of growth hormones, and improvement of stress tolerance.

These microorganisms play a double role in agroecosystems: they enhance plant growth while also reducing the presence of heavy metals and pesticides. They accomplish this through many mechanisms, including bioaccumulation, biosorption, biotransformation, and bioleaching. PGPMs play a crucial role in both the rehabilitation of polluted soils and the promotion of sustainable farming practices. They achieve this by increasing the availability of nutrients and boosting the ability of plants to resist toxic substances. This comprehensive method shows potential for

preserving soil health, guaranteeing crop output, and safeguarding environmental quality.

The study presents a detailed analysis of demographic and socioeconomic data, highlighting that most respondents (48%) are young farmers aged 19-30 years. This demographic is followed by those aged 31-45 (22%), 45-60 (12%), below 18 years (10%), and above 60 years (8%). Notably, over 48% of farmers have education levels below the 10th standard, with only 25% having graduated, and smaller percentages attaining intermediate (12%), higher school (10%), and post-graduation degrees (5%). The majority (84%) reside in rural areas and are primarily engaged in agriculture, whereas 16% of peri-urban farmers have additional occupations. Land holdings are predominantly small, with 52% having less than 1 hectare, 38% owning 1-2 hectares, 6% with 2-4 hectares, and only 4% possessing more than 4 hectares.

Farmers' knowledge of agrochemicals shows that 64% rely on dealer and expert recommendations for pesticide levels, while 32% follow label instructions. Pesticide application is predominantly done using hand-driven spray machines (88%), with only 10% adopting knapsack sprayers. The study reveals a concerning trend where 78% of farmers frequently reuse the same pesticide within a growing season, which can lead to overuse and resistance, whereas only 22% limit their application to a single instance. Higher education and pest management training are shown to reduce pesticide overuse.

Regarding attitudes and understanding of pesticides, 78% of farmers are unaware of the potential adverse effects, and 74% purchase pesticides without labels. Only 8% correctly interpret toxicity color codes. Despite this lack of awareness, 78% use some form of personal protective equipment (PPE), though the quality of PPE is not assessed. Acute pesticide toxicity symptoms are reported by 66% of respondents post-application. Moreover, improper pesticide disposal practices are prevalent, with 36% applying pesticides unnecessarily and 34% disposing of remnants in environmentally harmful ways.

The study also examines the contamination levels of heavy metals in vegetables and cereals. Analysis of 294 samples from various markets reveals that cadmium (Cd) and cobalt (Co) exceed maximum allowable concentrations (MAC) in certain vegetables from specific markets. Chromium (Cr) contamination is widespread, attributed to industrial wastewater irrigation, posing significant health risks from continuous intake of contaminated produce. Irrigation water and agricultural soil samples show high levels of toxic metals, with concentrations exceeding MAC in most cases, except for a few specific instances. Soil contamination varies significantly, with metals like lead (Pb), chromium (Cr), nickel (Ni), cadmium (Cd), and arsenic (As) found in elevated levels, likely due to industrial activities and agrochemical use.

In crop plants and edible parts, toxic metals such as Cd, As, Ni, Pb, and others are detected at high concentrations in tomatoes, spinach, and wheat. These levels often surpass MAC, posing health risks to consumers. Essential micronutrients like iron (Fe), zinc (Zn), and manganese (Mn) are also found in elevated levels, influenced by fertilization practices. Long-term consumption of contaminated vegetables is highlighted as a significant health concern.

Overall, the study underscores critical issues in the agricultural sector, including the prevalent use and mishandling of pesticides, lack of awareness about their adverse effects, and substantial contamination of vegetables with heavy metals. These factors collectively contribute to potential health risks for both farmers and consumers, underscoring the need for improved training, stricter regulations, and better management practices to ensure safe and sustainable agriculture.

The study assessed the daily intake (DI) of toxic metals and metalloids (TMMs) through the consumption of vegetables and cereals from various markets and agricultural firms in Lucknow. The analysis focused on metals such as As, Cr, Cd, Ni, Cu, Co, Fe, Mn, Zn, and Pb. DI values for vegetables from markets were higher than tolerable limits for most metals except As and Fe, which were particularly high in tomatoes and regions like Biswan, Khairabaad, and Shindholi. Conversely, DI values for agricultural firm produce were generally below tolerable limits. Despite current DI levels not posing an immediate health risk, prolonged exposure may lead to harmful effects. HQ and HI were used to assess non-carcinogenic risks. HQ values greater than 1 indicate potential health risks. The study found HQ values for TMMs in market vegetables exceeded safe limits, especially for Pb, Cu, Cd, Ni, Mn, Zn, and Co. HI values were significantly high across samples, suggesting considerable non-carcinogenic health risks. HQ rankings varied by market, with spinach, mint, and bitter gourd frequently showing higher risks.

Similar assessments for peri-urban agricultural farms revealed high HQ and HI values for most TMMs, except Cr and Zn, indicating significant health risks. HI values in vegetables and cereals from regions like Biswan, Khairabad, Sindhuali, Pasonda, and Mohanlal Ganj were alarmingly high, further emphasizing potential adverse health impacts from prolonged consumption. The study also evaluated carcinogenic risks (CRs) for metals like Pb, Cr, Cd, and Ni. CR values for Ni, Cr, and Cd exceeded acceptable limits, indicating a higher risk of cancer, whereas Pb posed a lesser risk. The findings were consistent across different markets and peri-urban areas, corroborated by recent medical reports linking high toxic metal levels to various health disorders.

BAF measures the accumulation of TMMs in plants from soil and irrigation water. The study found that BAF values were higher for metals like As, Fe, Mn, Cu, Zn, Co, and Pb when sourced from irrigation water compared to soil. This indicates a higher potential for human exposure to these metals through the food chain. Leafy vegetables showed particularly high accumulation rates for As, Cr, and Cd.

The contamination factor (C_{fc}) indicates the level of contamination of trace metals (TMs) in soil. In this study, the values for Cu, Co, Fe, and Mn are generally low, suggesting minimal pollution. However, Co shows considerable contamination in tomatoes and spinach from Khairabaad, Cu shows moderate contamination in Biswan, Khairabaad, and Mohanlal Ganj, Fe shows moderate contamination in Khairabaad, and Mn shows considerable contamination in Khairabaad and Shindholi. Zn shows moderate contamination overall, but very high contamination in the wheat fields of Shindholi, likely due to anthropogenic activities or the use of contaminated water for irrigation.

The C_{dg} values for Fe are less than 6, indicating low contamination across all studied areas. For Co, Cu, and Mn, the values range from 0 to 6 in Biswan, Shindholi, Pasonda, and Mohanlal Ganj, indicating low contamination, and 6 to 12 in Khairabaad, indicating moderate contamination. Zn shows a low degree of contamination in Pasonda (0 to 6) and high contamination in Shindholi (>24). The mCdg values for Cu, Co, Fe, Mn, and Zn are generally less than 2, demonstrating low contamination except for moderate contamination of Cu, Mn, and Co in Khairabaad and Shindholi, and very high contamination of Zn in Shindholi. This suggests heavy use of agrochemicals in these areas. The E_{fc} values reveal significant differences in

TM enrichment across the study areas. Cu and Zn show higher enrichment in peri-urban regions, while Co and Mn show low to moderate enrichment. Notably, Mn shows very high enrichment in tomato and spinach soils from Shindholi, and Co shows considerable enrichment in wheat soil from Shindholi. The I_{geo} values do not show a consistent trend in TM contamination levels due to anthropogenic activities. Fe, Cu, Mn, and Co show low contamination levels except for moderate contamination of Co, Mn, and Cu in Khairabaad, and Zn shows considerable contamination except for specific low-contamination cases in Khairabaad, Shindholi, Pasonda, and Mohanlal Ganj. The Mpi is used to monitor metal pollution levels. The study shows consistent variations in Mpi values, with Khairabad being strongly polluted and other regions like Biswan, Pasonda, Sindhuali, and Mohanlal Ganj showing low pollution levels. The ERI assesses the ecological risk posed by toxic metals in soil. The contamination factors of Pb, As, Cr, and Ni generally indicate low contamination, with exceptions in certain regions. Cd shows very high contamination across all samples. The ERI values range from low to moderate, with Khairabad and Sindhuali showing higher risks.

This section assesses the revival efficiency of beneficial soil microbes isolated earlier. Various bacterial and fungal strains were revived and evaluated for their tolerance to toxic heavy metals and pesticides, showing varied levels of resilience and functional activity. The selected microbes showed varying degrees of indole acetic acid (IAA) and ammonia production, contributing to plant growth promotion. Strains like ***Pseudomonas stutzeri, Bacillus filamentous****, and* ***Trichoderma lixii*** demonstrated significant activity. The microbial strains exhibited varying tolerance levels to organophosphate pesticides. Fungal strains showed higher tolerance compared to bacterial strains, with specific strains like ***A. luchuensis*** and ***P.***

polonicum showing notable resistance. The microbial strains also demonstrated tolerance to heavy metals like As, Pb, Cr, and Cd, with some strains showing higher tolerance levels up to 50 mg/L. Compatibility tests among the selected microbial isolates identified both positive and negative interactions. The results guided the selection of suitable microbial consortia for further studies. Microbial treatments significantly influenced soil properties, including pH, electrical conductivity, bulk density, total organic carbon, and available nitrogen, demonstrating the potential for soil quality improvement.

The study underscores the pressing need for multifaceted strategies to address the identified challenges in the agricultural sector. Key recommendations include:

- ✓ Enhanced Education and Training: Implement comprehensive training programs for farmers on the safe use and disposal of pesticides, the importance of following label instructions, and the health risks associated with improper pesticide use.
- ✓ Stricter Regulatory Measures: Enforce stringent regulations on the sale and use of pesticides, ensuring that all products are properly labeled and farmers are informed about their safe application. Regular monitoring of irrigation water and soil quality is essential to prevent heavy metal contamination.
- ✓ Sustainable Agricultural Practices: Promote the use of beneficial soil microbes and organic farming techniques to reduce the reliance on chemical inputs and improve soil health. These practices can enhance crop resilience and reduce the risk of contamination.
- ✓ Public Health Interventions: Implement public health initiatives to monitor and mitigate the health impacts of pesticide exposure and heavy metal contamination, particularly in vulnerable communities.

In conclusion, this study highlights the critical need for integrated approaches to improve agricultural practices, enhance farmer education, and protect public health. By addressing these challenges, it is possible to promote sustainable agriculture, ensure food safety, and safeguard the well-being of both farmers and consumers in the Lucknow region.