Intro

- Problem
  - Plastic pollution is a significant environmental concern due to the dramatic increase in plastic production over the last 70 years, soaring from 2 million tonnes in 1950 to 450 million yearly (Ritchie et al., 2024). Plastic waste that is not recycled, incinerated, or adequately contained in landfills can pollute the environment, with a significant portion ending up in the oceans and harming wildlife and ecosystems.
  - Bioremediation, a promising approach in environmental biotechnology, utilizes microbes to mitigate such pollution (Iwamoto & Nasu, 2001). This process involves degrading or detoxifying harmful substances by providing microorganisms with optimal conditions and nutrients (Bala et al., 2022). Bioremediation offers a cost-effective and environmentally friendly alternative to traditional chemical and physical remediation methods, which can be expensive and disruptive to ecosystems (Bala et al., 2022).
  - Despite its potential, bioremediation requires further research to enhance its reliability and safety (Iwamoto & Nasu, 2001). A deeper understanding of the complex interactions between microbes and pollutants and the impact of bioremediation on ecosystems is crucial. Continued research in this field can lead to more effective and sustainable bioremediation strategies for addressing various environmental pollutants, including emerging contaminants like pharmaceuticals and industrial waste (Bala et al., 2022).
- Thesis
  - This piece aims to synthesize existing information on the different bioremediation techniques (bacterial, enzymatic, mycoremediation, and phytoremediation) and encourage further research by simulating their hypothetical applications at scale.

Bacterial Bioremediation

- Strengths & Weaknesses
  - Bacteria are advantageous for bioremediation due to their wide availability, rapid growth, and adaptability to diverse environments. Their cell walls contain functional groups like aldehydes, ketones, and carboxyl groups that enable the biosorption of heavy metals (Alabssawy & Hashem, 2024). Additionally, some marine bacteria, like Bacillus cereus, can form biofilms, enhancing their bioremediation capabilities. Genetic engineering has expanded the potential of bacteria-based bioremediation by creating genetically modified microorganisms with enhanced pollutant removal abilities.
  - Despite their strengths, bacteria-based bioremediation faces limitations. Environmental factors like temperature, pH, and nutrient availability can significantly influence their effectiveness, and this approach is primarily suitable

for biodegradable pollutants - recalcitrant substances like chlorinated organic contaminants may remain unaffected (Alabssawy & Hashem, 2024). Using genetically modified microorganisms also raises legal, ethical, and biosafety concerns that require careful consideration.

- Research Opportunities
    - Alabssawy and Hashem (2024) highlight that most research on heavy metal bioremediation by marine organisms is limited to laboratory settings. They emphasize the need to scale these studies to real-world applications in contaminated soils, slurries, and aquatic systems. The authors also suggest that a deeper understanding of the molecular mechanisms behind metal mobilization, uptake, transport, and accumulation in these organisms is crucial for developing more effective bioremediation strategies. Additionally, they propose exploring novel approaches, such as combining nanotechnology with bioremediation and addressing biosafety concerns and regulatory frameworks for genetically modified microorganisms to enhance the applicability and acceptance of these technologies.

Enzymatic Bioremediation

- Strengths & Weaknesses
    - Enzyme-based bioremediation is a promising approach for removing emerging contaminants (ECs) like micro-nano plastics due to its environmentally friendly nature and rapid reaction times (Zhou et al., 2022). Enzymes like oxidoreductases and hydrolases have shown high efficiency in degrading various ECs, including pharmaceuticals, personal care products, and industrial dyes (Amaro Bittencourt et al., 2023).
    - However, challenges like the high cost of enzymes and the need for more research on large-scale applications in real-world environments remain (Amaro Bittencourt et al., 2023).
- Research Opportunities
    - Using immobilization techniques and genetic engineering can further enhance these enzymes' stability, reusability, and production, addressing some of the limitations associated with their application (Amaro Bittencourt et al., 2023).

Mycoremediation

- Strengths & Weaknesses
    - Mycoremediation, using fungi in bioremediation, presents a promising and eco-friendly approach to address environmental pollution. It offers several advantages, including cost-effectiveness, adaptability to diverse environments, and the ability to degrade a wide range of pollutants, including heavy metals and petroleum hydrocarbons (Bosco et al., 2019). Fungi possess unique

characteristics, such as a high adsorption and accumulation capacity for heavy metals, making them valuable agents for treating contaminated wastewater (Kumar & Dwivedi, 2021). Additionally, their capacity to colonize and thrive in extreme environments and their production of bioactive compounds and extracellular enzymes further enhance their effectiveness in bioremediation (Bosco et al., 2019).

    - However, mycoremediation also faces challenges and limitations. Research on the fungal degradation of aliphatic hydrocarbons, a common soil pollutant, remains limited, particularly in understanding the degradation pathways and enzymes involved (Antón-Herrero et al., 2023). The process can be time-consuming compared to some conventional treatments, and scaling up from laboratory to field scale presents difficulties in maintaining stable fungal-bacterial communities and optimizing conditions (Antón-Herrero et al., 2023). Moreover, a gap between basic research and industrial applications hinders the widespread adoption of mycoremediation technologies (Antón-Herrero et al., 2023). In some cases, the accumulation of toxic intermediates during degradation necessitates careful monitoring and management (Antón-Herrero et al., 2023).
- Research Opportunities
    - To fully harness the potential of mycoremediation, future research should prioritize investigating the fungal degradation pathways of aliphatic hydrocarbons, optimizing conditions for mycoremediation, and developing strategies for scaling up to field applications (Antón-Herrero et al., 2023). Exploring the use of spent mushroom substrate as a cost-effective inoculum and assessing the long-term impact of mycoremediation on soil health are also crucial areas for further investigation (Antón-Herrero et al., 2023). By addressing these challenges and expanding research efforts, mycoremediation can become a more robust and widely implemented solution for environmental restoration.

Phytoremediation

- Strengths & Weaknesses
    - Ionata et al. (2024) highlight that phytoremediation is a promising technology for removing environmental pollutants because it is a low-impact, sustainable, and cost-effective approach compared to physical and chemical methods. The authors emphasize that it is 5 to 13 times cheaper than other remediation techniques and allows for exploiting the produced biomass for biofuel and energy.
    - The authors also mention that plants' slow growth and detoxification rate can hinder their effectiveness, especially in heavily polluted areas. Additionally, the limited reach of plant roots may not address contamination at greater depths. The process is also susceptible to seasonal and weather fluctuations, impacting plant growth and remediation efficiency. Introducing non-native plant species for phytoremediation can disrupt the local ecosystem. Lastly, the safe disposal or

utilization of contaminated plant biomass poses a challenge to prevent further pollution.

- Research Opportunities
    - Ionata et al. (2024) suggest future phytoremediation research focus on developing hyperaccumulator species for remediation and bioenergy, optimizing post-phytoremediation biomass for biofuel, enhancing phytoremediation through genetic engineering, implementing agronomic practices to mitigate multiple toxicants, controlling toxic compound transit for industrial biorefinery, applying remediation in diverse field conditions, and developing profitable metal recovery methods. Additionally, they emphasize the need for socio-economic analyses to evaluate market impacts and occupational effects of phyto-derived products.

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