International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

Check for updates

Is biomining a feasible solution for E-waste management?

Trilochan Sethy, Md Mainul Sk *, Tapas Ranjan Patra and Mohammed Numan

Department of Geography, Rajendra University, Balangir, India, 767002.

International Journal of Science and Research Archive, 2024, 13(02), 3621-3627

Publication history: Received on 19 November 2024; revised on 26 December 2024; accepted on 28 December 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.2.2617

Abstract

With global growth in electronic waste (e-waste) at staggering rates, traditional methods of recycling pose significant health and ecological risks due to the use of energy intensive process and hazardous chemicals used. The use of microorganisms to extract valuable metals from waste, called biomining, is a promising alternative to conventional e-waste management practices. This study critically examined the feasibility of biomining as a sustainable alternative to recycling of e-waste. By comparing biomining with traditional methods, this study explored its environmental benefits, reduced chemical usage, and lower energy consumption, and its limitations, slower recovery rates and complex microbial processes. The study showed that biomining is most efficient when it is used to recover valuable metals such as gold and copper, but is less likely to be as efficient in the recovery of low-grade materials. In addition, it discussed the conditions under which it is conceivable that biomining is a sound solution and points out the importance of microbial optimization and appropriate economic and environmental conditions. Finally, the substantial areas for future research are presented, such as developing more efficient biomining processes, performing long term environmental impact assessment and life cycle analysis to assess the sustainability aspects of biomining as an e-waste management route.

Keywords: Biomining; E waste Management; Sustainable Recycling; Microbial Metal Recovery; Environmental Sustainability

1. Introduction

Electronic waste (e-waste) has grown to be one of the most serious environmental issues in the world in terms of the increasing speed of growth [1]. Unprecedented consumption of electronic devices and a fast turnover rate has produced million tons of e waste on an annual basis [2]. The world produced 53.6 million metric tons of e waste in 2019, of which an estimated 21% was formally recycled [3]. Valuable metals, including gold, silver, copper and palladium, can be extracted from e-waste, but so too, lead, mercury and cadmium pose considerable environmental and human health risks. Methods of traditional e waste management like landfilling and incineration do not only allow the material to be recovered as valuable resource, rather, it pollutes soil, air, and water [4]. However, these conventional practices are inefficient and that they result in harmful impacts, thus requiring immediate replacement by more sustainable and more effective solutions.

These challenges however have led to the emergence of biomining as a possible alternative to the treatment of e waste. Biomining is a technique in which microorganisms are employed to extract valuable metals from ores, waste materials or contaminated environments [5]. This is a more environmentally friendly, and cheaper, form of mining as standard methods involves harsh chemicals and lots of electricity. Biomining is a process that uses bacteria, fungi or algae to extract metals like gold, copper and nickel from low grade or trash ores [6]. Despite success in mining industries it is under explored if biomining can be applied for e-waste. Although the current literature points to the promise of biomining for e-waste management, it also reveals a gap in its performance for handling the complex composition of

* Corresponding author: Md Mainul Sk

electronic waste (Sarma and Zamboni, 2021). This raises a critical question: *Is biomining a feasible solution for e-waste management?*

The objective of this paper is to analyse the principles and processes of biomining and to assess its potential as a sustainable e-waste management technology. This study will analyse the benefits and limitations of biomining through a theoretical and critical analysis, compare it to traditional recycling techniques, and ultimately measure its economic and environmental viability. This research limits itself to the theoretical examination of biomining with regard to its possible application to e waste, without involving any primary data or performing empirical analysis. This study concentrates on critically reviewing the literature regarding the mechanisms involved in biomining and the feasibility of its application in e- waste management.

2. Literature Review

E-waste, a fast-growing waste stream globally, includes discarded electronic and electrical devices such as computers, televisions, cell phones and small electronic appliances [7]. A wide variety of materials including valuable metals, plastics, glass and hazardous materials (e.g., lead, mercury and cadmium) is present in these devices. Gold, silver, copper, palladium and rare earth metals of interest in e-waste can be recovered with specific recycling techniques [8]. In addition, e waste is rich in plastics and ceramics materials which are often not recovered well through heterogeneous materials [9]. Given the potential for resource recovery from e-waste, several innovative technologies are being discussed regarding how they can potentially provide a more sustainable approach, including biomining which can extract valuable metals from the e-waste without appreciably harming the environment [10].

Typically, traditional methods of e-waste management consist of mechanical processes, such as shredding, followed by chemical treatment techniques to get metal, which are smelting and electrochemical extraction [11]. These methods can be effective for high value metal recovery, but from an environmental and economic point of view, they have some significant drawbacks. One of the first problems with them is that they often create significant environmental pollution due to emission of toxic gases (dioxins, furans) and leachate pollution especially in the case of land filling disposal [12]. Additionally, these techniques are resource inefficient, recovering relatively little of the valuable materials contained in e waste. Methods for the recycling of e-waste (such as pyrolysis and recycling with blast furnace) are inefficient since they lack proper waste segregation and are complex to apply to e-waste which contain mixture of many metals and non-metals [13]. This highlights the necessity for more long lasting and efficient alternative option like biomining.

Biomining is a biological process utilising microorganisms to extract metal from ores, mine waste and contaminated environments. Bioleaching and bioaccumulation are the two main mechanisms of biomining. Bioleaching is the process of metals solubilization from ores or e waste materials (requiring only bacteria, fungi or algae) by means of the acidic or complexing agents produced by bacteria, fungi or algae [14]. Acidithiobacillus ferrooxidans and Leptospirillum ferrooxidans are important microorganisms involved in bioleaching: these able to oxidize sulfide metal and to release valuable metal (copper, gold) [15]. Another term, bioaccumulation, is the process in which microorganisms absorb and concentrate metals inside of their cells, most often for recovering precious metals like gold and silver [16]. Given their low environmental impact and ability to (discriminately) recover metals from e-waste containing complex low-grade combinations of metals, these biological processes present a healthy alternative route to recovery of metals from e-waste.

The application of biomining in e-waste management has been looked upon with promising results of recovering valuable metals from e-waste components. Several studies made use of microorganism to recover metal like gold, copper and palladium from e-waste. Recently, for example, researchers studied the bioleaching of gold from printed circuit boards (PCBs) using Acidithiobacillus species, which were shown to effectively release gold from complex matrices [17, 18]. Copper recovery has also been investigated by researcher, who demonstrate that Thiobacillus ferrooxidans can leach copper from e waste materials [19]. Moreover, as shown by Galasso, precious metals bioaccumulate within fungi in the utilization towards the recovery of palladium from electronic waste [20]. In these studies, we found that biomining is an effective and eco-friendly process for metal recovery from e waste. While microbial processes can be optimized to achieve higher efficiencies at greater scales, optimizing processes for the complex electronic waste mixtures remain challenging [21]. However, despite these challenges, the current research is indicating that biomining stands out as a genuine answer to sustainable e-waste administration.

3. Critical Analysis of Biomining for E-Waste Management

As an alternative method of e-waste management being environmentally friendly and able to recover valuable resources, biomining has emerged as potential alternative. However, of course it is important to critically evaluate this approach so as to understand both its advantages and its limitations.

3.1. Potential Benefits

One of the persuasive reasons which is in favour of where one could think of e-waste management with the help of biomining is that, it is comparatively less dangerous for the environment than the other methods of e waste management. Mechanical or chemical approaches are traditional e- waste recycling processes, which are energy intensive and produce harmful emission outputs such as greenhouse gases and toxic chemical effluents [22,23]. By using microorganisms to extract metals from e waste, known as biomining, it is achieved at a fraction of the energy compared to other methods, and pollution is minimal. It has been shown with studies that the use of microbes in metal extraction processes, for example, bioleaching, can be as much as twenty-five times lower in energy demands compared to other metal extraction processes, like smelting or incineration [24]. In addition, the use of biomining decreases the use of harsh chemicals such as cyanide or sulfuric acid, helping to reduce the likelihood of the creation of hazardous waste.

Apart from being a more natural process, biomining can be particularly useful to decontaminate valuable metals like gold, silver, copper and palladium that are found in e-waste [25]. Unlike traditional methods, where some valuable components can be lost during the recycling process, biomining recovers much greater volumes, even from complex electronic components, made of a mix of materials. Reducing reliance on primary mining and increasing useful material lifespans can be part of a circular economy, as this approach is intended to do. In addition, biomining techniques have the potential to be used for recovery of resources in e-wastes of varying complexity.

Although the initial setup for biomining operations may be expensive, operational costs over the long run might be cheaper than that of traditional recycling methods. In most of the biomining processes, they require fewer infrastructures since the process utilizes the natural action of microorganisms as opposed to the use of heavy machinery and high temperatures [26]. This leads to decreased energy consumption and lower operational costs in the long run and therefore, biomining is an encouraging fix for recovery of resources in areas with deficient admittance to capital or the ignored infrastructure. Further, the technique of biomining cuts back the requirement of chemicals such as sulfuric acid and cyanide, which otherwise results in the generation of hazardous waste.

3.2. Limitations and Challenges

Biomining could provide a potential benefit, but is faced with many technical hurdles in optimizing microbial processes for e-waste with complex and diverse compositions. Moreover, e-waste comprises multiple materials such as plastics, ceramics and different types of metals, that can hinder microbial activity [27]. While effective for some, the bioleaching process can be quite slow, especially for more refractory material, or when dealing with mixed waste streams. Consequently, long processing times will occur for this limitation, which is not always realistic for dealing with large scale operations. Biomining, well its generally thought to be more environmentally friendly than conventional methods, but it’s not risk free. Another issue is that the microbial degradation of e waste could also potentially release toxic substances into the air and surrounding soil and water sources. For instance, uncontrolled heavy metals such as mercury, arsenic and lead leaching can contaminate the environment [28]. Moreover, the industrial use of microorganisms in biomining may result in the unintentional release of harmful by products and therefore, further environmental damage caused by the process must be monitored and the waste handled appropriately. Consequently, robust environmental safeguards are implemented to mitigate these risks.

However economic and social factors also affect the feasibility of biomining for e waste management. While biomining may tend to be a less costly operational expense in the long run, setting up the infrastructure and research needed to get started will likely entail an initial capital investment that is quite large. Furthermore, there is still the public’s acceptance of biomining as a solution, since the technology is quite new, and its effectiveness has yet to be fully demonstrated in handling e-waste on a large scale [29]. Furthermore, as biomining has not yet been standardized, such that each regulated region has a gap in regulatory framework, it may hinder the dissemination of this technology. In order for biomining to emerge and scale up there will need to be supportive government policies and regulations. Unless there are public awareness campaigns to promote greater acceptance of this idea, it is conceivable that the biomining may not become a sustainable e waste recycling alternative.

4. Comparative Analysis: Comparing Biomining to Traditional Recycling Methods

Compared with traditional e-waste management techniques, the exploitation of biomass substrate for e-waste valorisation through biomining is highly resource and environment friendly. Typically, conventional methods like mechanical recycling or chemical processing use hazardous chemicals (for example, cyanide and acid) that can be environmentally and health hazardous [30]. And these processes can be energy intensive as well, resulting in high carbon footprints. On the other hand, biomining makes use of microorganisms to selectively recover valuable metals from e–waste by minimising chemical usage and reducing energy requirements [31]. However, traditional methods are much faster but result in toxic by-products and are far from ideal for complex e waste compositions [32]. Though biomining is eco-friendly, it takes a fairly long time to break down the e waste materials and the efficiency of the metal extraction largely depends upon the type of the e waste material and the microbial strains.

Feasibility of biomining varies depending on type of e-waste, microbial strains involved and local environmental conditions. Biomining has to be conducted under controlled conditions so as to moderately support microbial growth and metal leaching [33]. The concentration of recoverable metals in the e-waste is also a factor for affecting the potential scalability. High value metals such as gold and copper are suitable for biomining, while low grade waste may not be an economic prospect [34]. Additionally, implementation of biomining involves a consideration of the cost of technology relative to economic return of the extracted metals. Though, traditional methods may yet turn out to be economically feasible in areas with many environmental regulations and high labor costs [35].

In order to fully realize the potential of biomining, certain areas of research need to be studied. First of all, more efficient biomining processes (and their associated econometric modelling) must be created. Researchers should design future researches to focus on the optimization of microbial strains to improve the speed and yield of the recovery and also explore genetic engineering to improve the efficiency of the microbes. Furthermore, environmental impacts over long term of biomining processes require further assessment. Although biomining is less hazardous waste than traditional practices, the danger of secondary pollutants (bio leaching by products) still exists [36]. Long term environmental impacts of the byproducts of these on ecosystems and human health should be investigated in later studies.

5. Future Prospects of Biomining

E-waste management by biomining has a great potential as a sustainable solution; however, research and development are required to overcome limitations and challenges raised in this paper. Areas of research for improved economic viability and efficacy of biomining to recover valuable metals from e-waste consist of studying: 1) How to optimize the existing bioleaching biology to be less rapidly killed and respond to slight changes in conditions; 2) How to reduce energy use to reduce the cost of breaking down the metal bearing compounds; 3) How to integrate the chemistry for metal bearing compound breakdown into the existing biology to increase the cost effectiveness; 4) How to run the process in an anaerobic environment such that CO generated by the bacteria does not lead to polluting gas discharges; and 5) How to switch to an aerobic environment after completion of the breakdown and before metal recovery to use cheaper biotechnology involving bacteria; this not only economizes the process but also decreases the environmental impact of the process. In optimizing microbial processes for e waste treatment, one critical research area deals with this. Specifically, genetic engineering of microorganisms might increase their efficiency for recovering metals, and development of mixed microbial cultures might allow more effective leaching from less homogeneous waste materials. Scaling up biomining processes will require further research into the selection and cultivation of microorganisms that will flourish in e-waste environments. Biomining could be integrated with more traditional recycling methods, and further research could be performed in that direction.

More practical approaches for managing e waste on a large scale may be through hybrid approaches that combine the environmental benefits of biomining with efficiency of mechanical processing. By enabling the conventional recovery of high value metals, and the biomining of less valuable or complex materials, this could reduce waste disposal requirements and thus lower the environmental impact of metal production. In order to judge the long-term sustainability of biomining for e-waste management, a comprehensive life cycle analysis (LCA) and an environmental impact assessment (EIA) of biomining will be essential. Biomining appears to be an environmentally friendly, alternative mining process, but also requires an evaluation of its effect on local ecosystems and human health over time. To ensure that biomining is really a green alternative to conventional recycling methods, research needs to be conducted on the biomining's environmental footprint, including energy use, water consumption and waste generation.

6. Conclusion

This research critically examines biomining as a potential solution to the e-waste problem, and highlights the pros and cons of this method when compared against conventional recycling methods. The results show that biomining offers notable environmental advantages including a reduction of chemicals used and energy consumed with its feasibility however hinging on several factors: e-waste type and economic feasibility. These metals that are considered high value (gold and copper) are particularly promising biomining candidates but far slower rates of recovery and complex microbial processes are problematic. Finally, biomining proves its capability as a sustainable, green and healthier system for e-waste management in combination with other waste management practices. However, it requires further research to optimize the microbial processes and evaluates the long-term environment impacts and life cycle assessment to fully understand its potentials as large-scale solution. This means that further investment in research and development is necessary to move biomining from technology to viable commercial activity. Hybrid strategies combining traditional methods with those of biomining may be the way to manage e waste in the future to maximize recovery efficiency and environmental sustainability.

Compliance with ethical standards

Acknowledgments

The authors would like to extend heartfelt thanks to the Department of Geography, Rajendra University, Balangir, for providing access to laboratory facilities and resources necessary for this study.

Disclosure of conflict of interest

All authors declare that they have no conflict of interest related to the publication of this manuscript or with any institution or product mentioned in the study. No competing interests exist with products or entities that could influence the outcomes of the research.

References

[1] Hossain MS, Al-Hamadani SM, Rahman MT. E-waste: a challenge for sustainable development. J Health Pollut. 2015;5(9):3-11. https://meridian.allenpress.com/jhp/article/5/9/3/67510. Published 2015. Accessed July 19, 2024.

[2] Sk MM, Jinnah MA, Anjum R. Impact of E-Waste Management on Environmental Development: An Overview. Int Res J Educ Technol (IRJEdT). 2021;1(5):54-62. https://www.researchgate.net/profile/Md-Sk-7/publication/372440672. Accessed July 19, 2024.

[3] Seif R, Salem FZ, Allam NK. E-waste recycled materials as efficient catalysts for renewable energy technologies and better environmental sustainability. Environ Dev Sustain. 2024;26(3):5473-5508. https://doi.org/10.1007/s10668-023-02925-7.

[4] Premalatha M, Tabassum-Abbasi, Abbasi T, Abbasi SA. The generation, impact, and management of e-waste: State of the art. Crit Rev Environ Sci Technol. 2014;44(14):1577-1678. https://doi.org/10.1080/10643389.2013.782171.

[5] Schippers A, Hedrich S, Vasters J, Drobe M, Sand W, Willscher S. Biomining: metal recovery from ores with microorganisms. Geobiotechnol I: Metal-related Issues. 2014; 1:1-47. https://doi.org/10.1007/10_2013_216.

[6] Cozma P, Bețianu C, Hlihor RM, Simion IM, Gavrilescu M. Bio-Recovery of Metals through Biomining within Circularity-Based Solutions. Processes. 2024;12(9):1793. https://doi.org/10.3390/pr12091793.

[7] Liu K, Tan Q, Yu J, Wang M. A global perspective on e-waste recycling. Circ Econ. 2023;2(1):100028. https://doi.org/10.1016/j.cec.2023.100028.

[8] Sethurajan M, van Hullebusch ED, Fontana D, et al. Recent advances on hydrometallurgical recovery of critical and precious elements from end-of-life electronic wastes-a review. Crit Rev Environ Sci Technol. 2019;49(3):212-275. https://doi.org/10.1080/10643389.2018.1540760.

[9] Mainul S. Challenges in the management of single-use plastic carrier bags in Aligarh City: A study on sellers and consumer attitude. Int J Res Soc Sci. 2019;9(7):732-750.

https://www.indianjournals.com/ijor.aspx?target=ijor:ijrss&volume=9&issue=7&article=057. Accessed July 19, 2024.

[10] Hossain R, Sahajwalla V. Current recycling innovations to utilize e-waste in sustainable green metal manufacturing. Philos Trans A. 2024;382(2284):20230239. https://doi.org/10.1098/rsta.2023.0239.

[11] Kaya M. Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manag. 2016; 57:64-90. https://doi.org/10.1016/j.wasman.2016.08.004.

[12] Sk MM, Ali SA, Ahmad A. Optimal sanitary landfill site selection for solid waste disposal in Durgapur city using geographic information system and multi-criteria evaluation technique. KN J Cartogr Geogr Inf. 2020; 70:163-180. https://doi.org/10.1007/s42489-020-00052-1.

[13] Kumari R, Samadder SR. A critical review of the pre-processing and metals recovery methods from e-wastes. J Environ Manage. 2022; 320:115887. https://doi.org/10.1016/j.jenvman.2022.115887.

[14] Vo PH, Danaee S, Hai HTN, et al. Biomining for sustainable recovery of rare earth elements from mining waste: A comprehensive review. Sci Total Environ. 2024; 908:168210. https://doi.org/10.1016/j.scitotenv.2023.168210.

[15] Vera M, Schippers A, Hedrich S, Sand W. Progress in bioleaching: fundamentals and mechanisms of microbial metal sulfide oxidation–part A. Appl Microbiol Biotechnol. 2022;106(21):6933-6952. https://doi.org/10.1007/s00253-022-12168-7.

[16] Mishra A, Malik A. Recent advances in microbial metal bioaccumulation. Crit Rev Environ Sci Technol. 2013;43(11):1162-1222. https://doi.org/10.1080/10934529.2011.627044.

[17] Pourhossein F, Mousavi SM. A novel rapid and selective microbially thiosulfate bioleaching of precious metals from discarded telecommunication printed circuit boards (TPCBs). Resour Conserv Recycl. 2022; 187:106599. https://doi.org/10.1016/j.resconrec.2022.106599.

[18] Dong Y, Zan J, Lin H. Recovery of precious metals from waste printed circuit boards through bioleaching route: A review of the recent progress and perspective. J Environ Manage. 2023; 348:119354. https://doi.org/10.1016/j.jenvman.2023.119354.

[19] Arshadi M, Yaghmaei S, Mousavi SM. Optimal electronic waste combination for maximal recovery of Cu-Ni-Fe by Acidithiobacillus ferrooxidans. J Cleaner Prod. 2019; 240:118077. https://doi.org/10.1016/j.jclepro.2019.118077.

[20] Galasso C, Lekube X, Cancio I, et al. Marine fungi as potential eco-sustainable resource for precious metals recovery from electronic waste. Waste Biomass Valorization. 2022;1-10. https://doi.org/10.1007/s12649-021-01587-8.

[21] Chauhan G, Jadhao PR, Pant KK, Nigam KDP. Novel technologies and conventional processes for recovery of metals from waste electrical and electronic equipment: challenges & opportunities–a review. J Environ Chem Eng. 2018;6(1):1288-1304. https://doi.org/10.1016/j.jece.2018.01.032.

[22] Fawole AA, Orikpete OF, Ehiobu NN, Ewim DRE. Climate change implications of electronic waste: Strategies for sustainable management. Bulle of the Natio Resear Cen. 2023;47(1):147. https://doi.org/10.1186/s42269-023-01124-8.

[23] Sk MM, Qamar S, Sethy T. Solid Waste Management in Indian Perspectives: A Comprehensive Review. Humanit Soc Sci Stud. 2023;12(1):35-45. https://www.researchgate.net/profile/Md-Sk-7/publication/373737929. Accessed July 19, 2024.

[24] Izatt RM, Izatt SR, Bruening RL, Izatt NE, Moyer BA. Challenges to achievement of metal sustainability in our high-tech society. Chem Soc Rev. 2014;43(8):2451-2475. https://doi.org/10.1039/C3CS60440C.

[25] Islam A, Swaraz AM, Teo SH, et al. Advances in physiochemical and biotechnological approaches for sustainable metal recovery from e-waste: A critical review. J Cleaner Prod. 2021; 323:129015. https://doi.org/10.1016/j.jclepro.2021.129015.

[26] Gumulya Y, Zea L, Kaksonen AH. In situ resource utilisation: the potential for space biomining. Miner Eng. 2022; 176:107288. https://doi.org/10.1016/j.mineng.2021.107288.

[27] Van Yken J, Boxall NJ, Cheng KY, Nikoloski AN, Moheimani NR, Kaksonen AH. E-waste recycling and resource recovery: A review on technologies, barriers, and enablers with a focus on Oceania. Metals. 2021;11(8):1313. https://doi.org/10.3390/met11081313

[28] Sk MM. Assessing vulnerability of a solid waste management system through GIS and the rank sum method: A case study of Durgapur city, India. Adv in Environ Tech. 2025;11(1):36-62. https://doi.org/10.22104/AET.2024.7053.1939

[29] Arya S, Kumar S. Bioleaching: urban mining option to curb the menace of E-waste challenge. Bioengineered. 2020;11(1):640-660. https://doi.org/10.1080/21655979.2020.1775988

[30] Awasthi AK, Li J. An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE. Resour, Conser and Recy. 2017; 126:228-239. https://doi.org/10.1016/j.resconrec.2017.07.014

[31] Ilyas S, Lee JC. Biometallurgical recovery of metals from waste electrical and electronic equipment: a review. Chem Bio Eng Rev. 2014;1(4):148-169. https://doi.org/10.1002/cben.201400001

[32] Ilankoon IMSK, Ghorbani Y, Chong MN, Herath G, Moyo T, Petersen J. E-waste in the international context–A review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manag. 2018; 82:258-275. https://doi.org/10.1016/j.wasman.2018.10.018

[33] Gopikrishnan V, Vignesh A, Radhakrishnan M, et al. Microbial leaching of heavy metals from e-waste: opportunities and challenges. Biovalorisation of Wastes to Renewable Chemicals and Biofuels. 2020:189-216. https://doi.org/10.1016/B978-0-12-817951-2.00010-9

[34] Mainul SK, Ahmad A, Ali SA. Integrating public-private participation for sustainable solid waste management in Durgapur City: West Bengal. The Geographer. 2019; 66(2):57-66. https://www.indianjournals.com/ijor.aspx?target=ijor:tgr&volume=66&issue=2&article=006. Accessed July 19, 2024.

[35] Jerez CA. Biomining of metals: how to access and exploit natural resources sustainably. Microb Biotechnol. 2017;10(5):1191-1193. https://doi.org/10.1111/1751-7915.12792

[36] Zheng X, Lin H, Du D, et al. Remediation of heavy metals polluted soil environment: A critical review on biological approaches. Ecotoxicol Environ Saf. 2024; 284:116883. https://doi.org/10.1016/j.ecoenv.2024.116883