International Journal of Engineering Research and Science & Technology

www.ijerst.org

IF: 9.625

ISSN : 2319-5991



International Conference on Ensuring Global Food Safety-ICEGFS-2026

Vol. 22 No. 4(S) (2026)

ijerst.editor@gmail.com

editor@ijerst.com

International Conference on Ensuring Global Food Safety-ICEGFS-2026
ISSN 2319-5991 www.ijerst.com
© 2026 IJERST. All Rights Reserved

ENDOPHYTIC BACTERIA-MEDIATED NANOPARTICLE SYNTHESIS: A SUSTAINABLE APPROACH FOR ENVIRONMENTAL BIOREMEDIATION

Nagarathnamma.Yammanuri,
Government Degree college for women(A) Rayachoty
E.Mail: yammanuri751@gmail.com

ABSTRACT

Environmental contamination by uranium and other heavy metals poses a serious threat to ecosystem stability and human health, necessitating the development of efficient, cost-effective, and environmentally sustainable remediation strategies. Conventional remediation techniques are often associated with high operational costs, energy consumption, and secondary waste generation, highlighting the need for innovative alternatives. In this context, nanobioremediation, which integrates nanotechnology with biological remediation processes, has emerged as a promising approach for the removal, immobilization, and detoxification of environmental pollutants. Among various nanomaterials, biogenic nanoparticles, particularly manganese dioxide nanoparticles, have attracted considerable attention owing to their high surface area, adsorption capacity, and redox activity. The biological synthesis of nanoparticles using microorganisms offers an eco-friendly alternative to conventional physical and chemical methods by reducing the reliance on toxic chemicals and harsh reaction conditions. Endophytic bacteria are particularly valuable in this regard because of their ability to synthesize nanoparticles through intracellular and extracellular mechanisms mediated by bacterial enzymes, proteins, and secondary metabolites. In addition to nanoparticle synthesis, these bacteria contribute to phytoremediation by promoting plant growth, enhancing metal tolerance, producing siderophores and metal-binding compounds, and facilitating the biosorption, chelation, and transformation of heavy metals. Their interactions with nanoparticles may further improve contaminant immobilization, reduce metal bioavailability, and enhance the remediation potential of contaminated soils and wastewater. Previous studies have demonstrated the ability of endophytic bacteria, including *Bacillus* and *Pseudomonas* species, to synthesize nanoparticles with antimicrobial and other functional properties, highlighting their broader biotechnological potential. Despite these advances, further research is required to elucidate the mechanisms governing nanoparticle biosynthesis, metal–microbe interactions, long-term environmental stability, and potential ecotoxicological effects. Overall, endophytic bacteria-mediated nanoparticle synthesis represents a promising component of sustainable nanobioremediation, with potential applications in the management of uranium and heavy-metal contamination and the development of environmentally compatible remediation technologies.

Keywords: Endophytic bacteria, biogenic nanoparticles, nanobioremediation, heavy metals.

Received: 17-09-2026 Accepted: 22-10-2026 Published: 29-10-2026

INTRODUCTION

The escalating global concern regarding environmental contamination necessitates innovative and sustainable remediation strategies, particularly for radionuclides like uranium and other heavy metals, which pose significant threats to ecosystems and human health (Ghosh et al., 2021). Conventional methods for removal of heavy metals often involve costly and energy-intensive processes that can generate secondary

waste streams, highlighting the urgent need for environmentally benign alternatives (Karnwal& Malik, 2024). Bioremediation, leveraging the inherent capabilities of biological systems to detoxify or remove pollutants, has emerged as a promising approach (Samuel et al., 2022).

Nanomaterials, with their high surface area-to-volume ratio and unique physicochemical properties, can facilitate pollutant adsorption, degradation, or transformation (Rajput et al., 2022). Among various nanomaterials, manganese dioxide nanoparticles have garnered considerable attention for their exceptional redox properties, high surface area, and environmental compatibility, rendering them effective for the removal of heavy metals and radionuclides from contaminated water and soil (Patel et al., 2020). Biological synthesis of nanomaterials offers a green and sustainable alternative to traditional chemical methods, mitigating the use of toxic precursors and harsh reaction conditions. Microorganisms can be harnessed to synthesize nanomaterials through various mechanisms, including redox reactions, precipitation, and template-directed synthesis (Mandeep& Shukla, 2020). The employment of bacteria in the synthesis of metal and metal oxide nanoparticles offers a green alternative by being biocompatible, biodegradable and cost effective (Saxena et al., 2021).

Recently, nanotechnology has developed as a promising technology with multiple applications in various fields. The vital components of nanotechnology include nanomaterials and nanoparticles (NPs), which are established due to their extraordinary plasticity, flexible architecture, and greater performance (Khan et al., 2022; Soni et al., 2024; Malik et al., 2023). In general, nanomaterials are materials whose internal surfaces are non-scale in size. The external dimensions are in the nanoscale (usually 1–100 nm), because of that, nanomaterials have some special properties. These special properties provided the extraordinary adsorption capability and high reactivity to these NPs, making them consider these nanoparticles for removing heavy metal ions. One of the emerging fields of nanotechnology is the remediation of metal contaminants from the environment. To date, incredible studies have been carried out on nanomaterials to investigate their applications in heavy metal water treatment, and they have exhibited great potential as a promising alternative for adsorbing heavy metals from wastewater (Yang et al., 2019; Ishfaq et al., 2023).

The convergence of nanotechnology and bioremediation offers innovative solutions for environmental challenges, particularly in the removal of heavy metals and radioactive contaminants like polluted ecosystems (Samuel et al., 2022). Traditional methods often face limitations in terms of cost-effectiveness, efficiency, and environmental impact, necessitating the exploration of sustainable alternatives (Karnwal& Malik, 2024).

Nanobioremediation, integrating the principles of nanotechnology with biological processes, presents a promising avenue for enhancing the remediation of contaminated sites (Rajput et al., 2022). This approach leverages the unique properties of nanomaterials, such as their high surface area-to-volume ratio and enhanced reactivity, in conjunction with the metabolic capabilities of microorganisms to achieve efficient pollutant removal (Guerra et al., 2018). The in-situ generation of nanoparticles through microbial activity can be more advantageous than ex-situ methods, as it reduces the need for nanoparticle transport and dispersal, potentially minimizing environmental risks (Ghosh et al., 2021).

Advancements in the research have identified some novel cost-effective technologies, such as nano-remediation, microbial fuel cells, and

biosorption methods, as the most efficient for the removal of heavy metals from the environment (Sharma et al., 2018; Staszak& Regel-Rosocka, 2024; Syarifuddin et al., 2025). Among the various nanoparticles, biogenic nanoparticles (BNPs) synthesized using various biological organisms such as algae, bacteria, fungi, and plant extracts are gaining more importance, due to their surface area-to-volume ratios, functional activity(Azeez et al., 2023; Nain et al., 2025). These characters enable BNPs to sequestrate, immobilize, and reduce metal ions from the metal-contaminated sites (Minhas et al., 2023; Karnwal et al., 2024). Endophytic bacteria can synthesize the nanoparticles using either the extracellular or intracellular pathways. The bacterial enzymes, secondary metabolites bio-reduce the metal ions and synthesize the nanoparticles (Bogas et al., 2022).

Microorganisms, plants, and fungi were used in the room-temperature for the green production of nanoparticles.Nanoparticles created using biological means are preferred due to their special qualities (Singh. et al., 2015). Green synthesis is an eco-friendly, and low cost approach (Nadaroglu, et al 2017). This green method has several advantages over other methods, namely cost-effectiveness, simplicity, use of less temperature, the usage of less toxic material, moreover, it is compatible for medical and food applications (Korbekandi et al., 2009; Zheng et al., 2013).

These nanoparticles are used in a variety of fields, including biology, medicine, industry, and others. Recently, the use of nanoparticles in environmental remediation has increased tremendously. They have excellent potential for removing heavy metals and radioactive ions. Recent developments in the field have provided numerous potential for creating next-generation decontamination techniques for radioactive waste (Teow and Mohammad, 2019; Saikia et al., 2019; Yue Liu et al., 2019).

ENDOPHYTIC BACTERIA : NANOPARTICLE SYNTHESIS

In general, endophytic bacteria, which reside within plant tissues without causing apparent harm, represent a unique resource for bioremediation due to their ability to enhance plant growth, promote stress tolerance, and directly interact with pollutants in the rhizosphere and within plant tissues (Ramanathan et al., 2014). The convergence of nanotechnology and bioremediation, termed nanobioremediation, offers a synergistic approach to enhance the efficiency and scope of pollutant removal (Guerra et al., 2018; Rajput et al., 2022).

Microorganisms, including bacteria, fungi, and algae, possess inherent mechanisms for tolerating and interacting with heavy metals, making them valuable assets in bioremediation strategies (Ramanathan et al., 2014). Some microbes can dissolve metal minerals, increasing metal bioavailability, while others immobilize metals, reducing their bioavailability and toxicity (Fomina et al., 2004). Microbial-mediated redox reactions can alter the valence state of metals, influencing their solubility and mobility (Gaur et al., 2021). For example, bacteria can reduce complex toxic metals into soluble form, which precipitates out of solution, effectively immobilizing the contaminant. Studies reported that *Bacillus mycoides*endophytic isolated from *Viburnum grandiflorum* considerably improved wheat growth in Zn- and Ni-polluted soils by alleviating metal toxicity and stimulating antioxidant enzyme activities (Shahzad et al.,2024)

Recently, a group of microorganisms, endophytic bacteria that reside in the internal tissues of plants without causing any harm to the host plant, have been identified as key players in boosting the phytoremediation capability (He et

al., 2019; Liu et al., 2024; Liu et al., 2025). These microbes enter the plants through natural openings, move throughout them, and exert their effect (Tshikhudo et al., 2023). The endophytes develop a symbiotic relationship with their host plants. In contrast, plants provide shelter and nutrient requirements for the bacteria, and while the endophyte produces the phytohormones, metabolic enzymes to improve the nutrient uptake, growth, and development of the host plant. The endophytes also improve the biotic/abiotic stress resistance and detoxify the metals (Das et al., 2025). In general, endophytes adopt several mechanisms such as biosorption, chelation, redox transformations, and methylation to detoxify and reduce the uranium and other metal contaminants in plants (Bhardwaj, 2025; Liu et al., 2024).

The endophytes, such as *Bacillus* spp. and *Pseudomonas*spp, improved the concentrations of metal accumulation and also tolerance to higher concentrations of heavy metals such as Cd, Pb, and U when inoculated into the non-host plants *Brassica napus* and *Helianthus annuus*(Anitha et al., 2023; Liu et al., 2024). These bacterial species produce siderophores and organic molecules that can interact with the mineral elements and heavy metals, making them more soluble and phytoavailable. Endophytes' assistance helps to uptake the metals, detoxify the metal ions, trapping them in extracellular capsules, which minimizes the phytotoxicity and stabilizes the re-entry of metals into the environment (Riseh et al., 2022;Tsotetsi et al., 2022; Wu et al., 2024). (Table:1)

Bacterial Species	Type of nanoparticles	Location of nanoparticle	Size (nm)	Applications	Reference
Bacillus cereus	Silver	Extracellualr	20-40nm	Antibacterial	Sunkar et al.2012
Clostridium thermoaceticum	Cadmium	Extracellular	Crystal clumps	Cadmium effect on bacteria can be determined	Cunningham et al. 1993
Coryne bacterium sp.	Silver	Extracellular	10-15nm	Role of proteins involved in biosorption& bioreduction	Zhang et al. 2005
Desulfo bacteraceae	Zns	Intracellular	2-5nm	Remediation	Labrenz et al. 2000
Streptomyces sp.	Silver	Extracellular	10-17nm	Antimicrobial	Chauhan et al., 2013
Desulforibrioca ledoiensis	Zinc sulfide	Extracellular	~30nm	Photocatalysis	Sarangi et al., 2022
Enterococcus sp.	Cadmium sulphate	Extracellular	50-180nm	Antimicrobial	Rajeshkumar et al., 2014
Escherichia coli	Silver	Extracellular	10-15nm	Anti-cancer	Firdhouse et al., 2015

Table:1 Green Synthesis of Nanoparticles using Microorganisms and characteristic features of nanoparticles along with their applications.

Advancements in the research have identified some novel cost-effective technologies, such as nano-remediation, microbial fuel cells, and biosorption methods, as the most efficient for the removal of heavy metals from the environment (Sharma et al., 2018; Staszak& Regel-Rosocka, 2024; Syarifuddin et al., 2025). Among the various nanoparticles, biogenic nanoparticles (BNPs) synthesized using various biological organisms such as algae, bacteria, fungi, and plant extracts are gaining more importance, due to their surface area-to-volume ratios, functional activity(Azeez et al., 2023; Nain et al., 2025). These characters enable BNPs to sequestrate, immobilize, and reduce metal ions from the metal-contaminated sites (Minhas et al., 2023; Karnwal et al., 2024). Endophytic bacteria can synthesize the nanoparticles using either the extracellular or intracellular pathways. The bacterial enzymes, secondary metabolites bio-reduce the metal ions and synthesize the nanoparticles (Bogas et al., 2022).

The biosynthesis of nanoparticles (NPs) using endophytic bacteria has gained considerable attention as a sustainable and environmentally benign alternative to conventional physical and chemical synthesis approaches, particularly due to its potential applications in environmental bioremediation. For example, SwethaSunkar and C. ValliNachiyar (2012) described the green synthesis of silver nanoparticles (AgNPs) employing the endophytic bacterium Bacillus cereus isolated from Garciniaxanthochymus. The synthesized nanoparticles were stable and exhibited strong antimicrobial properties (Asian Pacific Journal of Tropical Biomedicine, DOI:10.1016/S2221-1691(13)60006-4).

Likewise, Ezzeldin Ibrahim et al. (2020) demonstrated that Pseudomonas poae, an endophyte obtained from garlic, facilitated the biosynthesis of AgNPs (around 20–45 nm) that effectively inhibited Fusariumgraminearum, underscoring their potential in plant disease control (Nanomaterials, DOI:10.3390/nano10020219). In another investigation published in Royal Society of Chemistry journal RSC Advances (2019, DOI:10.1039/C9RA04246F), endophytic Bacillus siamensis isolated from Coriandrumsativum was utilized for AgNP production, resulting in significant suppression of rice pathogenic bacteria along with enhanced plant growth.

Beyond agricultural applications, biologically synthesized nanoparticles contribute significantly to environmental bioremediation by functioning as efficient nanocatalysts and adsorbents for heavy metals, synthetic dyes, and various organic contaminants owing to their high surface area and reactivity. The emerging field of nanobioremediation combines microbial metabolic processes with nanoparticle technology to enhance the detoxification of polluted soils and wastewater systems. Endophytic bacteria further support phytoremediation by producing metal-binding compounds, antioxidative enzymes, and diverse bioactive metabolites, while the nanoparticles they generate can accelerate pollutant transformation and immobilization. Therefore, nanoparticle biosynthesis mediated by endophytes represents a promising and sustainable approach for environmental protection and remediation strategies.

Thus, the use of microorganisms to synthesize nanoparticles offers a green and sustainable approach compared to conventional chemical and physical methods, which often involve toxic precursors and energy-intensive processes (Patel et al., 2020). Endophytic bacteria, which reside within plant tissues without causing harm,

represent a particularly interesting group of microorganisms for nanobioremediation. They can promote plant growth, enhance nutrient uptake, and contribute to the detoxification of pollutants within the plant system. The utilization of natural processes in bioremediation, which can successfully biodegrade a range of pollutants, even persistent ones, could be a useful and effective method for reducing soil contaminations (Karmakar et al., 2024).

CONCLUSION

Endophytic bacteria-mediated nanoparticle synthesis represents a promising, eco-friendly, and sustainable approach to nanobioremediation for the removal and detoxification of uranium and other heavy metals from contaminated environments. By combining the unique physicochemical properties of biogenic nanoparticles with the metal-tolerance, biosorption, and plant growth-promoting capabilities of endophytic bacteria, this approach offers significant potential for enhancing phytoremediation and reducing environmental pollution. However, further research is needed to optimize nanoparticle synthesis, elucidate remediation mechanisms, and evaluate long-term environmental safety and effectiveness under field conditions. Overall, the integration of endophytic bacteria and nanotechnology could contribute to the development of efficient, cost-effective, and environmentally sustainable strategies for environmental bioremediation.

REFERENCES

1. Azeez, L., Adejumo, A. L., Oladejo, A. A., Olalekan, B., Basiru, S., Oyelami, O. K. and Abdullahi, M. (2025). Exploiting the synergistic influence of AgNPs-TiO2NPs: enhancing phytostabilization of Pb and mitigating its toxicity in Vignaunguiculata. International Journal of Phytoremediation, 27(2), 233-243.
2. Bogas, A. C., Henrique Rodrigues, S., Gonçalves, M. O., De Assis, M., Longo, E. and Paiva De Sousa, C. (2022). Endophytic microorganisms from the tropics as biofactories for the synthesis of metal-based nanoparticles: healthcare applications. Front in Nanotech, 4, 823236
3. Cunningham and l. L. Lundiejr., "precipitation of cadmium by *clostridium thermoaceticum*", applied and environmental microbiology, vol. 59, no. 1, pp. 7–14, 1993. DOI: 10.3390/plants1114178
4. Endophytic Bacillus siamensis strain C1 used for AgNP biosynthesis with antibacterial activity and plant growth enhancement, Journal: RSC Advances, DOI:10.1039/C9RA04246F
5. Ezzeldin Ibrahim, (2020)Green-synthesization of silver nanoparticles using endophytic bacteria isolated from garlic and its antifungal activity against wheat Fusariumgraminearum, Journal: Nanomaterials (Basel) Volume & Article:10(2):219 (2020) DOI10.3390/nano10020219
6. Ghosh, A., Hegde, R. V., Limaye, A. S., Thrilokraj, R., Patil, S. A., andDateer, R. B. (2023). Biogenic synthesis of δ-MnO_2 nanoparticles: a sustainable approach for C-alkylation and quinoline synthesis via acceptorless dehydrogenation and borrowing hydrogen reactions. Applied Organometallic Chemistry, 37, e7119. https://doi.org/10.1002/aoc.7119
7. Guerra, F. D., Attia, M. F., Whitehead, D. C., & Alexis, F. (2018). *Nanotechnology for environmental remediation: materials and applications*. **Molecules,** 23(7), 1760. DOI:**10.3390/molecules23071760.**
8. Ishfaq A, Shahid M, Nawaz M, Ibrar D, Hussain S, Shahzad T, Mahmood F, Rais A, Gul S, Gaafar A-RZ, Hodhod MS and Khan S (2023). Remediation of wastewater by biosynthesized manganese oxide nanoparticles and its effects on development

of wheat seedlings. Front. Plant Sci. 14:1263813. doi: 10.3389/fpls.2023.1263813.

9. Karnwal, A., Kumar Sachan, R. S., Devgon, I., Devgon, J., Pant, G., Panchpuri, M. and Kumar, G. (2024). Gold nanoparticles in nanobiotechnology: from synthesis to biosensing applications. ACS omega, 9(28), 29966-29982.
10. Karunakaran G, Sudha KG, Ali S. and Cho EB. (2023). Biosynthesis of Nanoparticles from Various Biological Sources and Its Biomedical Applications. Molecules.;28(11):4527. doi: 10.3390/molecules28114527
11. Khan, Y., Sadia, H., Ali Shah, S. Z., Khan, M. N., Shah, A. A., Ullah, N., Ullah, M. F., Bibi, H., Bafakeeh, O. T., Khedher, N. B., Eldin, S. M., Fadhl, B. M. and Khan, M. I. (2022). Classification, Synthetic, and Characterization Approaches to Nanoparticles, and Their Applications in Various Fields of Nanotechnology: A Review. Catalysts, 12(11), 1386. https://doi.org/10.3390/catal12111386.
12. Korbekandi, H., Iravani, S., &Abbasi, S. (2009). Production of nanoparticles using organisms. Critical reviews in biotechnology, 29(4), 279-306
13. Malik S, Muhammad K. and Waheed Y. (2023). Nanotechnology: A Revolution in Modern Industry. Molecules.;28(2):661. doi: 10.3390/molecules28020661.
14. Monika Singh (2022), ioprospects of Endophytic Bacteria in Plant Growth Promotion and Ag-Nanoparticle Biosynthesis, Journal: Plants (Basel)Volume & Article: 11(14):1787 (2022)
15. Nain, R., Patel, H., Chahar, M., Kumar, S., Rohilla, D. and Pal, M. (2025). Biosynthesized metallic nanoparticles for sustainable environmental remediation: mechanisms, applications, and future perspectives. Discover Chemistry, 2(1), 124.
16. Patel, A., Patel, D., and Vyas, R. (2023). Biotechnological potential of cellulolytic Paenibacillus species: Current status and future prospects. Journal of Applied Microbiol, 134(4), lxad001. https://doi.org/10.1093/jam/lxad001
17. Rajkumar, M., Sandhya, S., Prasad, M. N. V., and Freitas, H. (2012). Perspectives of plant-associated microbes in heavy metal phytoremediation. Biotechnology Advances, 30(6), 1562–1574. https://doi.org/10.1016/j.biotechadv.2012.04.011
18. S. Sunkar and c. V. Nachiyar, "biogenesis of antibacterial silver nanoparticles using the endophytic bacterium bacillus cereus isolated from garciniaxanthochymus," asian pacific journal of tropical biomedicine, vol. 2, no. 12, pp. 953–959, 2012.
19. Sagar, A., Rai, S., Ilyas, N., Sayyed, R. Z., Al-Turki, A. I., El Enshasy, H. A., and Simarmata, T. (2022). Halotolerantrhizobacteria for salinity-stress mitigation: Diversity, mechanisms and molecular approaches. Sustainability, 14(1), 490.
20. Salunke, B. K., Sawant, S. S., Lee, S. I., and Kim, B. S. (2015). Comparative study of MnO2 nanoparticle synthesis by marine bacterium Saccharophagusdegradans and yeast Saccharomyces cerevisiae. Applied microbiology and biotechnology, 99(13), 5419–5427.
21. Sharma, S. K., Sharma, M. P., Ramesh, A., and Joshi, O. P. (2012). Characterization of zinc-solubilizing Bacillus isolates and their potential to influence zinc assimilation in soybean seeds. Journal of Microbiology and Biotechnology, 22(3), 352-359.
22. Singh, M., Kaiser, J., & Hahn, H. (2015). Thick electrodes for high energy lithium ion

batteries. Journal of The Electrochemical Society, 162(7), A1196.

23. Singh, D. P., Singh, V., Gupta, V. K., Shukla, R., Prabha, R., Sarma, B. K., and Patel, J. S. (2020). Microbial inoculation in rice regulates antioxidative reactions and defense related genes to mitigate drought stress. Scientific reports, 10(1), 4818.
24. Soni A K. and Jha R K (2024). Nanotechnology's Applications and Potential in Various Fields. Cureus 16(4): e59234. doi:10.7759/cureus.59234.
25. Staszak, K. and Regel-Rosocka, M. (2024). Removing heavy metals: cutting-edge strategies and advancements in biosorption technology. Materials, 17(5), 1155.
26. Sweeney, c. Mao, x. Gao et al., "bacterial biosynthesis of cadmium sulfide nanocrystals," chemistry and biology, vol. 11, no. 11, pp. 1553–1559, 2004.
27. Sweeney, c. Mao, x. Gao et al., "bacterial biosynthesis of cadmium sulfide nanocrystals," chemistry and biology, vol. 11, no. 11, pp. 1553–1559, 2004.
28. SwethaSunkar& C. ValliNachiyar (2012) Biogenesis of antibacterial silver nanoparticles using the endophytic bacterium Bacillus cereus isolated from Garciniaxanthochymus Asian Pacific Journal of Tropical Biomedicine Volume & Pages:2(12):953-959(2012), DOI: 10.1016/S2221-1691(13)60006-4
29. Syarifuddin, S., Suryani, S. and Tahir, D. (2025). Global advances and innovations in bacteria-based biosorption for heavy metal remediation: a bibliom8etric and analytical perspective. Integrated Environ Assessment and Management, 21(3), 507-525.
30. Yang, C., Niu, D., Zhong, Y., Li, L., Lv, H., and Liu, Y. (2018). Adsorption of uranium by hydrous manganese dioxide from aqueous solution. Journal of Radioanalytical and Nuclear Chemistry, 315(3), 533-542.
31. Zhang L, Chen F, Zeng Z, Xu M, Sun F, Yang L, Bi X, Lin Y, Gao Y, Hao H, Yi W, Li M and Xie Y (2021). Advances in Metagenomics and Its Application in Environmental Microorganisms. Front. Microbiol. 12:766364. doi: 10.3389/fmicb.2021.766364.
32. Zheng, H., Wang, Z., Deng, X., Herbert, S., & Xing, B. (2013). Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. Geoderma, 206, 32-39.