

Earthworms Enhance the Soil Fertility, Soil Structure and Facilitate Nutrient Cycling

Ghulam Abbas^{1,*}, Muhammad Hasnain², Umm-E-Haseeba², Aqsa Sarwar¹, Javaria Altaf¹, Shehzad Ghayyur³, Rimsha Jameel⁴, Muhammad Khalid Iqbal⁵, Maham Wahid¹ and Fahad Rahul⁶

¹Department of Zoology, Government College University, Faisalabad 38040, Pakistan

²Department of Biochemistry, Government College University, Faisalabad 38040, Pakistan

³Department of Zoology Hazara University Mansehra, KP, Pakistan

⁴Department of Environmental Sciences, COMSATS University Islamabad

⁵Institute of Brain Disorders, Department of Physiology, Dalian Medical University Liaoning Province China

⁶Department of Environmental Science and Disaster Management, Gopalganj Science and Technology University, Gopalganj-8100, Bangladesh

*Corresponding author: abbas.aaa215@gmail.com

Abstract

The soil biota is more important for soil fertility and productivity. Nutrient cycling is a critical function that is important to life on earth. Earthworms are large component of fauna communities. The activities of earthworms are more important because it can enhance soil fertility and nutrients cycling. Through the rapid incorporation of detritus into mineral soil. Moreover, mucus production associated with water excretion in earthworms' guts also increased the activity of other beneficial soil microorganisms. In this chapter we explained the importance and significance of earthworm in soil fertility and structure. This is followed by the production of organic matter. So, in the short term, a more significant effect is the concentration of large quantities of nutrients (N, P, K, and Ca) that are easily assimilable by plants in fresh cast depositions. In addition, earthworms seem to accelerate the mineralization as well as the turnover of soil organic matter. Earthworms are known also to increase nitrogen mineralization, through direct and indirect effects on the microbial community. The increased transfer of organic C and N into soil aggregates indicates the potential for earthworms to facilitate soil organic matter stabilization and accumulation in agricultural systems, and that their influence depends greatly on differences in land management practices.

Keywords: Earthworms, Soil fertility, Soil structure, Nutrients, Nitrogen

Cite this Article as: Abbas G, Hasnain M, Umm-E-Haseeba, Sarwar A, Altaf J, Ghayyur S, Jameel R, Iqbal MK, Wahid M and Rahul F. 2025. Earthworms enhance the soil fertility, soil structure and facilitate nutrient cycling. In: Kausar R, Nisa ZU, Jamil M and Bashir I (eds), Integrated Health and Sustainability: Plants, Wildlife, and Genetic Resilience. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 197-202. <https://doi.org/10.47278/book.HH/2025.413>



A Publication of
Unique Scientific
Publishers

Chapter No:
25-027

Received: 07-Feb-2025
Revised: 13-Apr-2025
Accepted: 18-May-2025

Introduction

According to structural analysis, earthworm have longitudinal body divisions with setae in each body segment except the first two segments and external skeletal system is absent. Segmented bristle-bearing worms are therefore defined (Ansari et al., 2012). Another way of identifying *Eisenia fetida* and *Eisenia Andrei* is through refs segmented and the position of the Clitellum as listed by Curry & Schmidt (2007). The earthworms can be regarded as one of the most representative subcategories regarding their distribution in both natural and agricultural systems from the ecological and taxonomic viewpoints (Decaens et al., 2013). Setae, Clitellum size and prostomium are percentage consistent characters in earthworm species and the body colour, body size, first dorsal pore, spermathecal point and its position, genital mark and Clitellum size are variable characters in earthworm species (Hussain et al., 2022).

An evaluation of earthworms considering aspect of ecosystem engineers to soil strength is done (Lavelle et al., 2004; Guerra et al., 2021). Due to the fact that microorganisms play an important role in decomposition and molecular turnover (Aziz et al., 2023). It is wonderful because they help to make the soil fertility better, its structure and its chemical properties. As such, earthworms are useful since they improve the chemistry of the soil and help in cycling of nutrient tidbits (Sizmur & Richardson, 2020). Also, they possess the close receptors that allow them to quickly react to the soil chemicals. Hence, earthworms are often used as biomarkers for evaluation of the risks of polluted environments (De Vaufléury & Gimbert, 2013).

Landscape utilization and management, burrowing activity and feeding behavior also predispose the content of heavy metals in hummin and organic (Morgan & Morgan, 1999). The distribution of earthworms depends with the texture and the type of soil. Earthworms were employed as biotechnological warrants for soil quality inasmuch as they avoid agricultural land that is treated to synthetic fertilizers or pesticides (Kousar & Akhter, 2020). Earthworms are recognized to magnify pollution in so far as they are known for this function (De Vaufléury & Gimbert, 2013; Garcia-Gomez et al., 2014). Dermal loading of heavy metals occurs on the earthworm as well as ingestion because they dwell in soil and feed on it (Lanno et al., 2004; Schnug et al., 2015). It consists of decomposable vegetable matter deposited at a 30 cm soil depth (Kousar & Akhter, 2020).

They claimed that, for 80 percent, the soil fauna are the earthworms that stand to benefit immensely from the variety of different birds and other vertebrate species (Sivakumar, 2015; Edwards & Arancon, 2022). Soil biota here is utilized because the concentration of pollutants in the tissues of the biotic components is proportional to the population densities of the pollutant in the soil (Nannoni et al., 2011). Biotic component is also used here as an index of pollution of the soil. Ecosystem engineers and/or pioneers, as earthworms are characterized, are characterized by increased sensitivity to toxic substances. Earthworms, therefore, have the ability to survive in soils containing heavy metals, and can thus endure severely objectionable environmental conditions concerning the soil (Lavelle et al. 2004; Becquer et al., 2005; Maity et al., 2008; Eijsackers, 2010).

Since earthworms play a crucial role on the fertility of the soil they are considered as some of the most important soil organisms. These are known as the farmer's friend, bioindicators, the ones who create habitats, geo-browsers, and agricultural crop growers. Earthworms are mainly hermaphrodite, have a low growth rate with references of exceptions on earthworms found in the leaf litter zone. Earthworms live two to eight years and breed each year and lay eight to twelve cocoons depending with the species. In the sexually mature specimens, there is an organizing that takes the form of a belt around the body, called the clitellum. Earthworms are established all over the global habitat and best fit in the eco-regions that differ from extreme cold and deserts with 3000 recognized species of geo worms. Preferred in mid-heavy and loamy sandy soil. They face many challenges associated with heavily clayey soils which hold a lot of moisture and sandy soils which lack the same. Breeding and emergence occur during March-April and second half of September-October specially in temperate latitudes (Brown et al., 2003). They move to areas at lower altitudes and reproduce during spring as well as extreme temperature conditions they undergo aestivation. Lumbricals terrestris the nightcrawler, can extend for a range of 20m. These are vital in the sustainable breaking down of organic matter and conversion into minerals. They play a very important role as far as soil enriching is concerned with respects to the chemistry, physical and biological characteristics of the soil (McLean et al., 2000; Bohlen et al., 2004).

Earthworms increase ecosystem properties such as pedologic, structural, hydrological, nutrient cycling, productive, climatic, and pollutant bioremediation and cultural areas (Blouin et al., 2013). They have been used in traditional medicine for a longer time due to the presence of different chemical compounds (Grdisa et al., 2013). A miscellany of about 60-70% protein serves as a sort of complementary feed for fishes and poultrys (Moreki & Tiroesele, 2012; Olele & Okonkwo 2012). For specific people particularly the Ye'Kuana Amerindians in Venezuela they are a staple food and are consumed both fresh and fermented into smoked varieties (Paoletti et al., 2003).

Microorganisms and Earthworms

Therefore, the impacts of earthworms are mainly confined to soil microorganisms. The microbes exist and proliferate in earthworms (Hoang et al., 2016). Hence, the soil improved with the earthworms is generally considered to have higher microbial load and richness. Previous work has explored the ability of earthworms to affect the decomposition of soil organic matter (SOM). It is well appreciated that soil fauna plays a crucial role for skeletal processes; however, its indirect impacts on microbial abundances and the interactions between microorganisms and fauna are not well understood. Organisms at the microscopic level are mostly involved in the biochemical breaking down of various materials. Therefore, because earthworms and their casts directly ingest micro decomposer organisms and promote microbial colonization of the newly exposed ground by fragmentation of organic matter, can exert top-down control of microbial decomposers. In many cases, microorganisms are used as food by earthworms. The amount taken and the ability to metabolize micronutrients and microorganisms vary depending on the worm species, the food items, and these systems significantly affect its extent and nature of earthworm uptake (Brown & Doube, 2004; Singleton et al., 2003; Johnsen et al., 2005; Kuczak et al., 2006).

Earthworms alter the Microbial Community in the soils

The composition of the gut microflora in earthworm depends with species (Krisstuek et al., 1993). Ecosystems are important as they provide the substrates on which earthworms feed and which supports many microorganisms. Ways used by earthworms and microbes in the cycling of humified organic matter and in the chelation of specific metal ions have been explained. It was found that earthworms demonstrated a capability of ingesting soil microbes as nutrient source. Since carbon is essential to earthworm growth and reproduction and nitrogen is received from the litter, grit, and microbes. Some microbes were chosen selectively while others were completely excluded from the diet. The role of microbes and earthworms in decomposition especially in humification process is well understood. Microbial load is therefore directly connected with microbial metabolic activity as well as with higher concentrations of humic acids. Actinomycetes are densely distributed in all feed substrates and more prominently in the gut and cast of the four studied earthworm species, as they are involved in the formation of humus and humic acid. They significantly increase nutrient levels in a technically mineralized manner through enzyme produced by microbial activities and earthworms (Egert et al. 2004; Sampedro et al. 2007; Koubova et al. 2015).

Impact of Earthworm on plant growth and Soil Enrichment

Animals as small as earthworms have been recognized since 1881 and Darwin introduced the habits and effects of worms on the ground in his book, *The Formation of Vegetable mould* (Aswathanarayana, 2003). Terrestrial macro-invertebrates either transport, digest or produce biogenic structures that enhance conditions for soil fertility and turnover rate of biopolymers to molecules in the soil organic matter and nutrients. Soil organic matter contributes to the status of mobile carbon source and is an indispensable component of the cultivated horizon. These subcomponents enhance the physical properties of the soil, water regime, cation balance, and pH respectively. Soil aggregates were put forward for this purpose because they are thought to improve plant health, decay and nutrient cycling. Among the soil fauna assemblages, earthworms are recognized to be the most essential component. It is suggested that they are related to the fertility and productivity of the organic matter in anthropogenic, utilized tropical soils. Among the invertebrates examined earthworms significantly modified the content of organic matter, mineralization and humification in these ecosystems. Various genera of the earth-worm show certain categorization with reference to their behavioral pattern with respect to the soil bio-tunneling and the fertility (Le Bayon et al., 2002; Egert et al., 2004; Gopal et al., 2017; Hoeffner et al., 2018).

Earthworms Play a Great Role in Enriching the Fertility of the soil

Through this burrow, the earthworm brings nutrients to the soil surface and drops foods on the nutrient layer. An element of a vermicompost forage supplies soil nutrients to support earthworms and at the same time incorporate organic matter into ground. Some of these are: composting to break down putrescible organic matter, making nutrients available to plants, and keeping the structure of the soil (Hallaire et al., 2000; Jegou et al., 2001; Blouin et al., 2007). Better aggregation, better soil penetration, and improved production of organic matter facilitate nourishment of the plants by the earthworms. Many worms take a large amount of the substrate with them and worms comprise only 5% to 10 % of the total population (Sander et al., 2008; Valckx et al., 2010). It is expelled in the form of small dough balls which are similar to the excreta of earthworms and contains nitrogen, potassium, micronutrients (Singleton et al., 2003; Johnsen et al., 2005; Dominguez et al., 2010; Fujii et al., 2012).

Soil structure formation and hence related water holding capacity that is influenced by interactions at micro as well as macro level between the large biota namely, plant root, earth worms, organic matter and Tillage operations. It is also well explained how the worm affects the reorganization of soil structures to a great extent because the worm has necessarily a limited ability to assimilate while tunneling, ingesting and excreting the soil material (Johnsen et al., 2005; Gomez- Brandon et al., 2011; Fujii et al., 2012).

It is believed that earthworms produce casts about 40-100 t/ha of its ecosystem services in engineering the soil structures (Singleton et al., 2003; Brown & Doube, 2004). Depending on the type of treatment, 18-42% soil particles can undergo change and migrate to the macro aggregate fraction within a two-month duration. The presence of earthworm species enhances the property of soils associated with porosity (Aira et al., 2009). An analysis established that the fine fraction of soil aggregates with sizes below 0.4mm was higher in the treatments without earthworm than in those treatments employing the use of earthworm. The impact was contingent upon cast and soil degradation as well as the qualitative interaction between the endogeic earthworm and the porosity of the soil since it dictates water circulation over the land (Atiyeh et al., 2000; Chan et al., 2004; Johnsen et al., 2005).

Earthworms play a Significant role Regarding the Alteration of soil Ecosystems

Earthworm is an influential ecological counterpart for enhancing the terrestrial nutritive recycling processes and microbial functioning through its priming effects. Many foods containing mucigenic products activate microorganisms, hormone-like products resulting into regulation of plant gene favoring energy conservation. The “Sleeping Beauty Paradox” clears up an interdependence between earthworms, and the microorganisms living in the soil. The earthworm kiss in the drilosphere of freely dialysable glycoproteins is bestowing in the dormant bio form which is prevailing at appropriate environmental conditions (Brown et al., 2003; Lavelle et al., 2004; Curry & Schmidt, 2007). It may also be used to choose or activate the correct set of microbes within the gut if the earthworm’s enzymes are inadequate to digest the particular type of soil. This process is not least beneficial for the incorporation of bacterial taxa into the soil which are decomposing organic matter in order to feed the earthworms or for denitrifying bacteria living within the anaerobic environment of the gut. The functions in which these microorganisms play is critical; hence the consequences of earthworms on oil-related microbes are important in determining the earthworm’s influence on ecosystem functions. Earthworms influence growth and nutrition of plants directly and primarily through modifying microbial ecology (Monroy et al., 2008; Nechitaylo et al., 2010; Chapuis-Lardy et al., 2010; Fujii et al., 2012; Shan et al., 2013).

Earthworms (class: Subclass Oligochaeta includes nearly 800 genera and about 8000 species, and individual worms may constitute 90% of the invertebrate inhabitants of the soil. These are ubiquitous, abundant, and unrivaled in their functions of nutrient cycling, described as ‘keystone species within the soil ecological context and recognized as ‘edaphic engineers’ (Brown & Doube, 2004; Lavelle et al., 2004; Begna, 2022). Because earthworms affect basic measures and processes of soil structure, organic matter, and nutrient cycling involved in the formation of soil structures, carbon storage, and nutrient cycling (Lavelle et al., 2004). Therefore, optimization of the utilization and administration of the off-type earthworm bio-resources may encompass several economic and ecological values linked with the major global challenges connected with the land, food and environment (Briones & Schmidt, 2004).

Role of Soil Earthworms in Biological Make-up and Nutrient Cycling

Earthworms are important in the first stage of particle breakdown of organic materials and in the constructive breaking down that make nutrient cations within the organic material to be recycled. It is also found that they have a higher consumption rate of the surface organic matter than any other soil organisms. They secrete them as molds which are nutrient bearing, soluble in water and easily available to plants. Soil macro-feeding is done by earthworms as they consume soil, crop residues, plant litter and partially decomposed matter take the material from the upper surface of the soil to the lower surface where it is ingested and fragmented (Edwards & Arancon, 2022). The excreta or feces are called cast, and these appear on the surface of the soil along worm burrows or in the interstadial of particle arrangements in a loamy matrix. Through ingestion and digestion of organic matter as well as mineralization of nutrient elements earthworms apparently participate in the formation of humus and the content of both essential and trace minerals of the soil. The earthworm effects can be further divided into two categories, namely the earthworm physiology and mobility; they also contribute to the processes of creation and arrangement of Bio-oriented soil particles and surfaces, which are also known as bio – particles and comprises of aggregate and pore issues which influences the soil flow properties, nutrient availabilities and plant growth (Scheu, 2003; Coq et al., 2007).

The use of manure and earthworms is generally used in techniques of fertilization in cycling of carbon, nitrogen and phosphorus in soil (Li et al., 2016; Vidal et al., 2023). The use of manure as a mode of increasing soil fertility is considered environmentally friendly as well. Such attributes suggest that the application of OC influences such soil factors as pH and nutrient cycling, microbial mineralization, and therefore crop productivity (Zhang et al., 2013). To improve fertility of the soil and to reduce level of arsenic content in the soil, people often use the earth worm like *E. foetida*, which affects soil properties and also it is used as bio mark of the condition of the soil (Hoang et al., 2016). Through mineralization, earthworms transform organic nitrogen into a mineral form through urine and mucus as well as decomposing tissues; the earthworm casts contain a massive mineral nitrogen. Much of the ammonium nitrogen contained in these casts stand ready to be transformed into nitrate nitrogen by nitrobacteria (Fonte et al., 2007; Giannopoulos et al., 2010).

Bioremediation and Pollution Control

Terrestrial soil macrofauna are therefore bioindicators of land utilization, soil fertility and pollution status (Peres et al., 2011). These have been attributed to length, slow rate of soil turnover, and slow rate of soil recolonization as issues that define their potential as bioindicators (Mo et al., 2012; Xu et al., 2018). Some species of earthworms do not die by contacting heavy metal contaminated soils because they have resistance to it, they perform their ecological functions and reproduce. This kind of translocation process may be due to the plants sensing cadmium as a toxic metal and thus its transport out of the roots. This leads to the general activation of defense mechanism for instance encapsulation within the vacuole or the cell walls. After that plants may be harvested, and material that may be incinerated. Secondly, Phyto-stabilization can be local within a zone of influence defined by the plant root system. In this case, water pollution is anchored to the roots and address through various mannerisms such as synthesizing specific compounds that capture heavy metals (Orgiazzi et al., 2016).

Recommendation for Future Research

In the majority of the ecosystem researches exploring casts influence on the nutrient cycling and soil structure most intact cast “workers” adopt surface-casting species with an impractical representation of the natural field conditions offering only a few concrete cases of buried casts. Thus, this evaluation will greatly improve the understanding of nutrient dynamics in earthworm burrow systems and in-soil casts on plant growth. The ecological implication of below ground casting alike the surface casting for the earth worm species is just as important concerning nutrient amendment in respect of biological repair of impacted and unstable natural environments. Therefore, more studies are needed in this field to expand the knowledge on the involvement of earthworms in nutrient cycling with intention to establish better effective sub processes for soil management.

References

- Ahmed, N., & Al-Mutairi, K. A. (2022). Earthworms effect on microbial population and soil fertility as well as their interaction with agriculture practices. *Sustainability*, 14(13), 7803.
- Aira, M., Monroy, F., & Domínguez, J. (2009). Changes in bacterial numbers and microbial activity of pig slurry during gut transit of epigeic and anecic earthworms. *Journal of Hazardous Materials*, 162(2-3), 1404-1407.
- Ansari, A. A., & Saywack, P. (2011). Identification and classification of earthworm species in Guyana. *International Journal Zoology Research* 7(1), 93-99, 2011.
- Aswathanarayana, U. (2003). *Mineral resources management and the environment*. 1st edition, pp 216. CRC Press. <https://doi.org/10.1201/9780203971222>
- Atiyeh, R. M., Domínguez, J., Subler, S., & Edwards, C. A. (2000). Changes in biochemical properties of cow manure during processing by earthworms (*Eisenia andrei*, Bouché) and the effects on seedling growth. *Pedobiologia*, 44(6), 709-724.
- Aziz, S., Altaf, J., Khalil, A., Khalil, H., Jehangir, K., & Awan, F. S. (2023). Human cancer risk due to chromium and its bioaccumulation in physids in Central Punjab, Pakistan. *Environmental Science and Pollution Research*, 1-13.
- Becquer, T., Dai, J., Quantin, C., & Lavelle, P. (2005). Sources of bioavailable trace metals for earthworms from a Zn-, Pb-and Cd-contaminated soil. *Soil Biology and Biochemistry*, 37(8), 1564-1568.
- Begna, T. (2022). Impact of drought stress on crop production and its management options. *International Journal of Research in Agronomy*, 8, 1-13.
- Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., & Brun, J. J. (2013). A review of earthworm impact on soil function and ecosystem services. *European Journal of Soil Science*, 64(2), 161-182.
- Bohlen, P. J., Scheu, S., Hale, C. M., McLean, M. A., Migge, S., Groffman, P. M., & Parkinson, D. (2004). Non-native invasive earthworms as agents of change in northern temperate forests. *Frontiers in Ecology and the Environment*, 2(8), 427-435.
- Briones, M. J. I., & Schmidt, O. (2004). Stable isotope techniques in studies of the ecological diversity and functions of earthworm communities in agricultural soils. *Recent Research Developments in Crop Science*, 1, 11-26.
- Brown, G. G., & Doube, B. M. (2004). Functional interactions between earthworms, microorganisms, organic matter, and plants. In *Earthworm ecology* (pp. 213-239). CRC Press.
- Brown, G. G., Benito, N. P., Pasini, A., Sautter, K. D., de F Guimarães, M., & Torres, E. (2003). No-tillage greatly increases earthworm populations in Paraná state, Brazil: The 7th international symposium on earthworm ecology· Cardiff· Wales· 2002. *Pedobiologia*, 47(5-6), 764-771.
- Chan, K. Y., Baker, G. H., Conyers, M. K., Scott, B., & Munro, K. (2004). Complementary ability of three European earthworms (Lumbricidae) to bury lime and increase pasture production in acidic soils of south-eastern Australia. *Applied Soil Ecology*, 26(3), 257-271.
- Chapuis-Lardy, L., Brauman, A., Bernard, L., Pablo, A. L., Toucet, J., Mano, M. J., & Blanchart, E. (2010). Effect of the endogeic earthworm *Pontoscolex corethrurus* on the microbial structure and activity related to CO₂ and N₂O fluxes from a tropical soil (Madagascar). *Applied Soil Ecology*, 45(3), 201-208.
- Coq, S., Barthès, B. G., Oliver, R., Rabary, B., & Blanchart, E. (2007). Earthworm activity affects soil aggregation and organic matter dynamics according to the quality and localization of crop residues—an experimental study (Madagascar). *Soil Biology and Biochemistry*, 39(8), 2119-2128.
- Curry, J. P., & Schmidt, O. (2007). The feeding ecology of earthworms—a review. *Pedobiologia*, 50(6), 463-477. De Vaufléury, A., & Gimbert, F. (2013). *Bioaccumulation, bioamplification des polluants dans la faune terrestre-Un outil pour la biosurveillance des écosystèmes* (p. 682). EDP sciences.
- Decaens, T., Porco, D., Rougerie, R., Brown, G. G., & James, S. W. (2013). Potential of DNA barcoding for earthworm research in taxonomy and ecology. *Applied Soil Ecology*, 65, 35- 42.

- Dominguez, J., Aira, M., & Gómez-Brandón, M. (2010). Vermicomposting: earthworms enhance the work of microbes. *Microbes at Work: from Wastes to Resources*, 93-114.
- Edwards, C. A. & Arancon, N. Q. (2022). Earthworm Ecology: Communities. In *Biology and Ecology of Earthworms*, 151-190.
- Egert, M., Marhan, S., Wagner, B., Scheu, S., & Friedrich, M. W. (2004). Molecular profiling of 16S rRNA genes reveals diet-related differences of microbial communities in soil, gut, and casts of *Lumbricus terrestris* L. (Oligochaeta: Lumbricidae). *FEMS Microbiology Ecology*, 48(2), 187-197.
- Eijsackers, H. (2010). Earthworms as colonisers: primary colonisation of contaminated land, and sediment and soil waste deposits. *Science of the Total Environment*, 408(8), 1759-1769.
- Elvira, C., Sampedro, L., Benitez, E., & Nogales, R. (1998). Vermicomposting of sludges from paper mill and dairy industries with *Eisenia andrei*: a pilot-scale study. *Bioresource Technology*, 63(3), 205-211.
- Fonte, S. J., Kong, A. Y., van Kessel, C., Hendrix, P. F., & Six, J. (2007). Influence of earthworm activity on aggregate-associated carbon and nitrogen dynamics differs with agroecosystem management. *Soil Biology and Biochemistry*, 39(5), 1014-1022.
- Fujii, K., Ikeda, K., & Yoshida, S. (2012). Isolation and characterization of aerobic microorganisms with cellulolytic activity in the gut of endogeic earthworms. *International Journal of Microbiology*, 15(3), 121-30.
- Furlong, M. A., Singleton, D. R., Coleman, D. C., & Whitman, W. B. (2002). Molecular and culture-based analyses of prokaryotic communities from an agricultural soil and the burrows and casts of the earthworm *Lumbricus rubellus*. *Applied and Environmental Microbiology*, 68(3), 1265-1279.
- García-Gómez, C., Esteban, E., Sánchez-Pardo, B., & Fernández, M. D. (2014). Assessing the ecotoxicological effects of long-term contaminated mine soils on plants and earthworms: relevance of soil (total and available) and body concentrations. *Ecotoxicology*, 23, 1195-1209.
- Giannopoulos, G., Pulleman, M. M., & Van Groenigen, J. W. (2010). Interactions between residue placement and earthworm ecological strategy affect aggregate turnover and N₂O dynamics in agricultural soil. *Soil Biology and Biochemistry*, 42(4), 618-625.
- Gómez-Brandon, M., Aira, M., Lores, M., & Domínguez, J. (2011). Epigeic earthworms exert a bottleneck effect on microbial communities through gut associated processes. *PLoS One*, 6(9), e24786.
- Gopal, M., Bhute, S. S., Gupta, A., Prabhu, S. R., Thomas, G. V., Whitman, W. B., & Jangid, K. (2017). Changes in structure and function of bacterial communities during coconut leaf vermicomposting. *Antonie Van Leeuwenhoek*, 110, 1339-1355.
- Grdisa, M., Grsic, K., & Grdisa, M. D. (2013). Earthworms-role in soil fertility to the use in medicine and as a food. *Invertebrate Survival Journal*, 10(1), 38-45.
- Guerra, C. A., Bardgett, R. D., Caon, L., Crowther, T. W., Delgado-Baquerizo, M., Montanarella, L., & Eisenhauer, N. (2021). Tracking, targeting, and conserving soil biodiversity. *Science*, 371(6526), 239-241.
- Hoang, D. T., Razavi, B. S., Kuz'yakov, Y., & Blagodatskaya, E. (2016). Earthworm burrows: kinetics and spatial distribution of enzymes of C-, N- and P-cycles. *Soil Biology and Biochemistry*, 99, 94-103.
- Hoeffner, K., Monard, C., Santonja, M., & Cluzeau, D. (2018). Feeding behaviour of epi-aneic earthworm species and their impacts on soil microbial communities. *Soil Biology and Biochemistry*, 125, 1-9.
- Hussain, M., Liaqat, I., Mubin, M., Nisar, B., Shahzad, K., Durrani, A. I., & Rubab, S. (2022). DNA barcoding: Molecular identification and Phylogenetic analysis of pheretimoid earthworm (*Metaphire sp.* and *Amyntas sp.*) based on mitochondrial partial COI gene from Sialkot, Pakistan. *Journal of Oleo Science*, 71(1), 83-93.
- James, S. W. (1991). Soil, nitrogen, phosphorus, and organic matter processing by earthworms in tallgrass prairie. *Ecology*, 72(6), 2101-2109.
- Johnsen, A. R., Wick, L. Y., & Harms, H. (2005). Principles of microbial PAH-degradation in soil. *Environmental Pollution*, 133(1), 71-84.
- Koubova A., Chroňáková, A., Pižl, V., Sánchez-Monedero, M. A., & Elhottová, D. (2015). The effects of earthworms *Eisenia* spp. on microbial community are habitat dependent. *European Journal of Soil Biology*, 68, 42-55.
- Kousar, S., & Akhter, M. (2020). Population density of earthworm's species in the mango and date palm orchards in Faisalabad, Pakistan. *Journal of Entomology and Zoology Studies*, 8(2), 1210-1214.
- Kuczak, C. N., Fernandes, E. C., Lehmann, J., Rondon, M. A., & Luizao, F. J. (2006). Inorganic and organic phosphorus pools in earthworm casts (*Glossoscolecidae*) and a Brazilian rainforest Oxisol. *Soil Biology and Biochemistry*, 38(3), 553-560.
- Lanno, R., Wells, J., Conder, J., Bradham, K., & Basta, N. (2004). The bioavailability of chemicals in soil for earthworms. *Ecotoxicology and Environmental Safety*, 57(1), 39-47.
- Lavelle, P., Charpentier, F., Villenave, C., Rossi, J. P., Derouard, L., Pashanasi, B., & Bernier, N. (2004). Effects of earthworms on soil organic matter and nutrient dynamics at a landscape scale over decades. In *Earthworm ecology* (pp. 145-160). CRC press.
- Le Bayon, R. C., Moreau, S., Gascuel-Oudoux, C., & Binet, F. (2002). Annual variations in earthworm surface-casting activity and soil transport by water runoff under a temperate maize agroecosystem. *Geoderma*, 106(1-2), 121-135.
- Li, Y., Tang, H., Hu, Y., Wang, X., Ai, X., Tang, L., & Qiu, J. (2016). Enrofloxacin at environmentally relevant concentrations enhances uptake and toxicity of cadmium in the earthworm *Eisenia fetida* in farm soils. *Journal of Hazardous Materials*, 308, 312-320.
- Lone, M. I., He, Z. L., Stoffella, P. J., & Yang, X. E. (2008). Phytoremediation of heavy metal polluted soils and water: progresses and perspectives. *Journal of Zhejiang University Science B*, 9(3), 210-220.
- Maity, S., Roy, S., Chaudhury, S., & Bhattacharya, S. (2008). Antioxidant responses of the earthworm *Lampito mauritii* exposed to Pb and Zn contaminated soil. *Environmental Pollution*, 151(1), 1-7.
- McLean, M. A., & Parkinson, D. (2000). Introduction of the epigeic earthworm *Dendrobaena octaedra* changes the oribatid community and microarthropod abundances in a pine forest. *Soil Biology and Biochemistry*, 32(11-12), 1671-1681.
- Mishra, C. S. K., Samal, S., & Samal, R. R. (2022). Evaluating earthworms as candidates for remediating pesticide contaminated agricultural soil: A review. *Frontiers in Environmental Science*, 10, 924480.
- Mo, X., Qiao, Y., Sun, Z., Sun, X., & Li, Y. (2012). Molecular toxicity of earthworms induced by cadmium contaminated soil and biomarkers

- screening. *Journal of Environmental Sciences*, 24(8), 1504-1510.
- Monroy, F., Aira, M., & Domínguez, J. (2008). Changes in density of nematodes, protozoa and total coliforms after transit through the gut of four epigeic earthworms (Oligochaeta). *Applied Soil Ecology*, 39(2), 127-132.
- Moreki, J. C., & Tiroesele, B. (2012). Termites and earthworms as potential alternative sources of protein for poultry. *International Journal for Agro Veterinary and Medical Sciences*, 6, 368-76.
- Morgan, J. E., & Morgan, A. J. (1999). The accumulation of metals (Cd, Cu, Pb, Zn and Ca) by two ecologically contrasting earthworm species (*Lumbricus rubellus* and *Aporrectodea caliginosa*): implications for ecotoxicological testing. *Applied Soil Ecology*, 13(1), 9-20.
- Nannoni, F., Protano, G., & Riccobono, F. (2011). Uptake and bioaccumulation of heavy elements by two earthworm species from a smelter contaminated area in northern Kosovo. *Soil Biology and Biochemistry*, 43(12), 2359-2367.
- Nechitaylo, T. Y., Yakimov, M. M., Godinho, M., Timmis, K. N., Belogolova, E., Byzov, B. A., & Golyshin, P. N. (2010). Effect of the earthworms *Lumbricus terrestris* and *Aporrectodea caliginosa* on bacterial diversity in soil. *Microbial Ecology*, 59, 574-587.
- Olele, N. F., & Okonkwo, J. C. (2012). Replacement of fish meal with graded levels of earthworm meal in the diet of fingerlings: effect on feed and growth parameters. *Journal of Agricultural Science and Technology: A*, 2(7A), 901.
- Orgiazzi, A., Bardgett, R. D., & Barrios, E. (2016). *Global soil biodiversity atlas* (pp. 176-pp).
- Page, V., Le Bayon, R. C., & Feller, U. (2006). Partitioning of zinc, cadmium, manganese and cobalt in wheat (*Triticum aestivum*) and lupin (*Lupinus albus*) and further release into the soil. *Environmental and Experimental Botany*, 58(1-3), 269-278.
- Paoletti, M. G., Buscardo, E., Vanderjagt, D. J., Pastuszyn, A., Pizzoferrato, L., Huang, Y. S., & Glew, R. H. (2003). Nutrient content of earthworms consumed by Ye'Kuana Amerindians of the Alto Orinoco of Venezuela. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 270(1512), 249-257.
- Parelho, C., dos santos Rodrigues, A., Bernardo, F., do Carmo Barreto, M., Cunha, L., Poeta, P., & Garcia, P. (2018). Biological endpoints in earthworms (*Amyntas gracilis*) as tools for the ecotoxicity assessment of soils from livestock production systems. *Ecological Indicators*, 95, 984-990.
- Parthasarathi, K., & Ranganathan, L. S. (2000). Aging effect on enzyme activities in pressmud vermicasts of *Lampito mauritii* (Kinberg) and *Eudrilus eugeniae* (Kinberg). *Biology and Fertility of Soils*, 30, 347-350.
- Peres, G., Vandenbulcke, F., Guernion, M., Hedde, M., Beguiristain, T., Douay, F., & Cluzeau, D. (2011). Earthworm indicators as tools for soil monitoring, characterization and risk assessment. An example from the national Bioindicator programme (France). *Pedobiologia*, 54, S77-S87.
- Ritsema, C. J., & Dekker, L. W. (2000). Preferential flow in water repellent sandy soils: principles and modeling implications. *Journal of Hydrology*, 231, 308-319.
- Sampedro, L., & Whalen, J. K. (2007). Changes in the fatty acid profiles through the digestive tract of the earthworm *Lumbricus terrestris* L. *Applied Soil Ecology*, 35(1), 226-236.
- Scheu, S. (2003). Effects of earthworms on plant growth: patterns and perspectives: The 7th international symposium on earthworm ecology. Cardiff. Wales. 2002. *Pedobiologia*, 47(5-6), 846-856.
- Schnug, L., Ergon, T., Jakob, L., Scott-Fordsmand, J. J., Jøner, E. J., & Leinaas, H. P. (2015). Responses of earthworms to repeated exposure to three biocides applied singly and as a mixture in an agricultural field. *Science of the Total Environment*, 505, 223-235.
- Shan, J., Liu, J., Wang, Y., Yan, X., Guo, H., Li, X., & Ji, R. (2013). Digestion and residue stabilization of bacterial and fungal cells, protein, peptidoglycan, and chitin by the geophagous earthworm *Metaphire guillelmi*. *Soil Biology and Biochemistry*, 64, 9-17.
- Shen, Y. (2010). Earthworms in Traditional Chinese Medicine: (Oligochaeta: Lumbricidae, Megascolecidae). *Zoology in the Middle East*, 51(sup2), 171-173.
- Singleton, D. R., Hendrix, P. F., Coleman, D. C., & Whitman, W. B. (2003). Identification of uncultured bacteria tightly associated with the intestine of the earthworm *Lumbricus rubellus* (Lumbricidae; Oligochaeta). *Soil Biology and Biochemistry*, 35(12), 1547-1555.
- Sivakumar, S. (2015). Effects of metals on earthworm life cycles: a review. *Environmental Monitoring and Assessment*, 187, 1-16.
- Sizmur, T., & Richardson, J. (2020). Earthworms accelerate the biogeochemical cycling of potentially toxic elements: Results of a meta-analysis. *Soil Biology and Biochemistry*, 148, 107865.
- Vidal, A., Blouin, M., Lubbers, I., Capowiez, Y., Sanchez-Hernandez, J. C., Calogiuri, T., & van Groenigen, J. W. (2023). The role of earthworms in agronomy: Consensus, novel insights and remaining challenges. *Advances in Agronomy*, 181, 1-78.
- Vorpahl, P., Moenickes, S., & Richter, O. (2009). Modelling of spatio-temporal population dynamics of earthworms under wetland conditions—an integrated approach. *Ecological Modelling*, 220(24), 3647-3657.
- Xu, H. J., Chen, H., Wang, X. L., Zhang, Y. L., Wang, J. J., Li, N., & Li, Y. T. (2018). Earthworms stimulate nitrogen transformation in an acidic soil under different Cd contamination. *Ecotoxicology and Environmental Safety*, 165, 564-572.
- Zhang, W., Hendrix, P. F., Dame, L. E., Burke, R. A., Wu, J., Neher, D. A., & Fu, S. (2013). Earthworms facilitate carbon sequestration through unequal amplification of carbon stabilization compared with mineralization. *Nature Communications*, 4(1), 2576.