



REVIEW ARTICLE

Soil health responses to microplastic contamination in agroecosystems: A comprehensive review

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Abstract

The contamination of terrestrial ecosystems, particularly agricultural soils by microplastics has emerged as a significant concern for soil health and sustainable agricultural production. Recent estimates indicate that microplastic concentrations in terrestrial habitats may be 4–23 times higher than those reported in aquatic environments, emphasising the importance of understanding their impacts on soil ecosystems. Microplastic smaller than 5mm affects the physical characteristics of the soil, which negatively impacts the capability of the soil to supply nutrients to plants, which in turn affects the productivity of crops. The presence of plastics alters microbial composition and productivity, affecting nutrient turnover and the breakdown of organic matter. It has been shown in laboratory tests that there was a decrease in nitrogen-fixing bacteria and the total microbial density in soil samples containing microplastics. Furthermore, these pollutants affect the lives of some fauna in the soil, like earthworms, by inhibiting their growth. The other factor contributing to the severity of soil pollution risks is the nature of microplastics to adsorb and transport hazardous compounds such as organic contaminants and toxic metals, which are present in the food web and have profound impacts on both human well-being and the biosphere. More effort and a prompt response are necessary to accurately estimate the extent of microplastics and their persistent effects on soil health, remediate the problems associated with plastic use in the agricultural sector and effectively control plastic use in agriculture. This review critically synthesises current knowledge on the sources of microplastics and their effects on soil physical, chemical and biological health indicators while highlighting key research gaps relevant to sustainable agricultural management.

Keywords: agricultural practices; heavy metals; microbes; microplastics; plastic mulch; soil health; soil properties

Introduction

Synthetic polymers are widely used in daily life, with approximately 359 million tonnes of plastics produced annually. According to earlier projections, global plastic production is expected to reach 12000 million tonnes by 2050 (1). In general, developing nations either dump or throw away a substantial volume of plastic waste. Agricultural and industrial sectors usually prefer plastic products due to their portability, durable and cheaper to purchase (2). Discarded plastics in the atmosphere are classified according to their size into macro, meso, micro and nano-plastics, ranging from nanometers to centimeters in size (Fig. 1). They have been reported in many matrices, including soils, coasts and wetlands, sea and the digestive tracks of vertebrates (3).

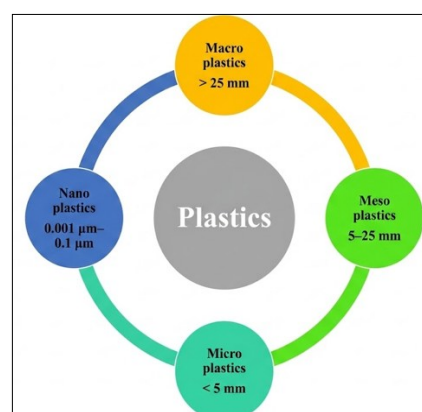


Fig. 1. Types of plastics.

Soil health is defined as the ability of a soil to continue to function as a living ecosystem that supports plants, animals and humans (4, 5). Healthy soils influence biogeochemical processes, promote biodiversity, sequester carbon and sustain productivity. However, soil health is being compromised by micro plastics contamination from anthropogenic activities such as plastic mulching, sewerage irrigation, plastic coated fertilisers, soil amendments and inappropriate plastic waste disposal. Through human activities including uses of mulching with plastic material (6), sewage irrigation (7), soil amendment application, plastic-coated fertilisers (8) and littering (9). This is because the intrusion of disposal through the decomposition of plastic has caused contamination of soil throughout the world.

Soil health plays a significant role in the assessment of the environment and management processes to encourage the sustainable use of soils. The three main soil health metrics are soil physical, chemical and biological properties, all of which are necessary to ensure soil functions and agricultural productivity (10, 11). There are multiple sources of anthropogenic microplastics in agricultural soil that have been reported in numerous studies (12). Soil health encompasses various physical, chemical and biological processes and the assessment of these indicators offers a holistic view of how microplastic pollution affects soil-based systems. Nevertheless, the currently available literature provides less information about the effect of microplastic pollution on the soil (13).

Therefore, there is an urgent need to assess all the influences of plastic materials pollution in soil on other soil health indicators. The aim of this review is to critically examine the effects of micoplastics contamination on physical, chemical and biological health indicators of agroecosystems and their implications for sustainable agroecosystems management. Moreover, the review highlights existing knowledge gaps and explores the potential for reducing the effects of microplastic contamination on soil health and sustainable management of agriculture. Results of this review are anticipated to aid for future studies and help inform development of sustainable strategies to combat microplastic contamination in agricultural soils.

Materials and Methods

Review approach

The current work is a narrative review aimed at integrating the available scientific materials in the context of the research of the issue of microplastics in agricultural soils and their related impact on the soil physical, chemical and biological characteristics. The author chose a narrative approach, as the studies related to the topic of soil microplastics are still in their transitional stage and may be defined by a high level of methodological heterogeneity, such as differences in the types of polymers, the size of particles, concentrations and soil specifics.

Literature collection

The availability of the relevant literature in the form of peer-reviewed works was accessed in the Scientific databases such as Scopus, Web of Science, ScienceDirect and Google Scholar. The search was focused on the studies that covered the microplastic contamination in terrestrial and agricultural soils. The keywords were used in various combinations and included microplastics, agricultural soils,

soil health, soil physical properties, soil chemical properties, soil biological properties, plastic mulching, biosolids, compost and irrigation water.

Selection criteria

It was based on the relevance of the studies to the agroecosystems and soil health. Inclusion criteria included:

- i) investigations that indicate the existence, sources or routes of microplastics in agricultural soils
- ii) research that measures the impacts of microplastics on physical, chemical or biological indicators of soil and
- iii) articles that mention mitigation/management of plastic contamination of the agricultural system.

Data compilation and interpretation

The characteristics of microplastics (type, size and concentration), sources, experiment conditions and reported responses of the soil were gathered using information of the chosen studies. The data extracted were synthesised and segmented into themes according to the areas of soil physical, chemical and biological properties, qualitatively. The research results were discussed by making comparative evaluation of the received results to establish similar patterns, opposite reactions and gaps in the knowledge. None of the new experimental information or statistical meta-analysis was done.

Quality assessment of selected studies

The selected studies were analysed using a narrative synthesis method, but methodological quality was assessed during interpretation of the data. The study design (i.e., laboratory, greenhouse, or field experiments), the way the experiments were conducted, the relevance of the results to agricultural soils, the size of the experimental sample, the clarity of presentation of the results and consistency of results with other published studies were given consideration. Greater emphasis was placed on peer-reviewed studies with well-defined experimental protocols and reproducible outcomes, while results from preliminary or short-term investigations were interpreted with appropriate caution.

Scope of the review

The main addressing of the review is on agricultural soils and microplastic inputs that refer to agricultural practices and land management. Direct quantitative comparisons were restricted by differences in experimental science and reporting across examinations. The narrative synthesis, however, gives an overall assessment of the reactions of soil health to microplastic pollution in agroecosystems.

Results and Discussion

Sources from agriculture

In terrestrial ecosystems, agriculture is known to be a large source of micro-plastics. Use of plastic based materials in crop production has helped to facilitate a significant build-up of micro-plastics in agricultural soils. They come from both direct agricultural activities and external sources, leading to the long-term contamination of soils. The major direct sources of microplastic contamination in agricultural soils are illustrated in Fig. 2.

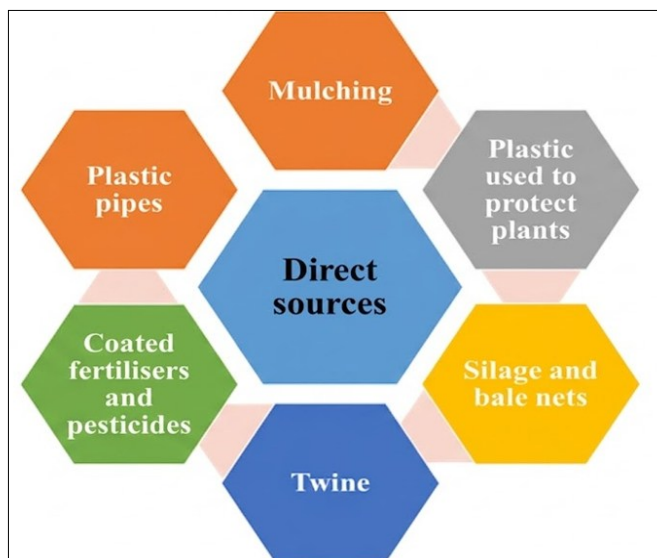


Fig. 2. Direct sources of microplastics.

Direct sources

Mulching: Plastic mulch application increases temperature on land and water availability for plants while at the same time reducing weed competition (14). Recent years have seen problems associated with the widespread application of plastic mulches due to their slow breakdown leading to high levels of micro plastics in soils used for agricultural production (15).

Plastics used in shade nets: Microplastics are also found in shade nets, greenhouses, polytunnels and wind barriers made of plastics and plastic-based non-woven fabrics in the sample. Only a limited number of studies have examined the release of microplastics from shade nets, greenhouses and other plastic-based crop protection materials. Microplastic levels in soil have been found to be higher under greenhouse than open field crops (7).

Silage and bale nets: One of the earliest studies on the farm scale indicated that plastics used for silage wrapping can release microplastics to livestock feed, from which they can enter agricultural soil via animal excreta (16).

Twine: Polypropylene twine is a very commonly used twine in the production of crops and handling in the bales. Tying the pods together with string is very common and typically leaves behind some string that breaks into microplastics upon decomposition in the field. Twine is an important source of soil contamination, with about 11 % of agricultural plastics used in this way in the European Union (17).

Encapsulated fertilisers and pesticides: The primary agrochemicals industry uses the properties of plastic polymers as encapsulators of slow-release fertilisers and pesticides. Once the nutrients are released, the polymer coating will remain in the soil which can eventually break down into microplastics (18).

Plastic pipes: Irrigation pipes are a relatively small source of microplastics, but during long-term use, they can be subject to weathering and mechanical damage, which can also lead to the release of plastic particles. Further field research is needed to estimate their contribution into soil pollution (19).

Indirect sources

The principal indirect pathways through which microplastics enter agricultural soils are summarised in Fig. 3.

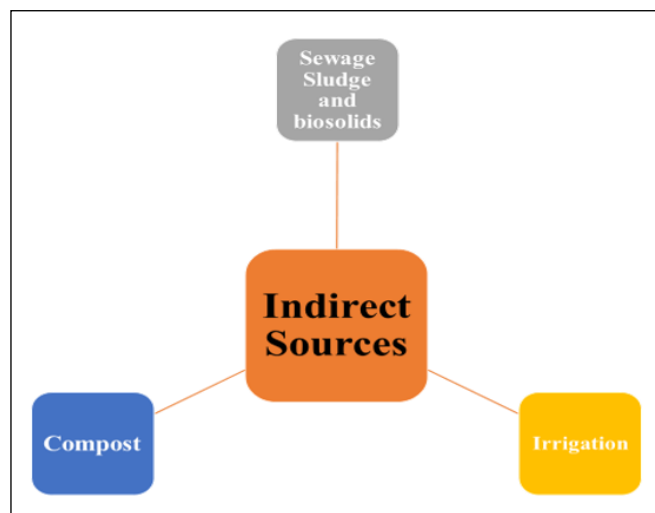


Fig. 3. Indirect sources of microplastics.

Sewage sludge and biosolids: Microplastics in sewage sludge and biosolids are from domestic wastewater, industrial discharges and urban runoff (20–23). These materials are important indirect sources of microplastic contamination when used in agriculture as organic amendments.

Compost: There are several studies that have found that compost can be an indirect source of microplastics due to the potential presence of plastic after composting from municipal organic waste (24, 25). More specifically, the work of previous researchers demonstrated that polyester, polypropylene and polyethylene comprised between 70 and 80 % of the overall quantity of plastic particles ascertained in organic manure (25).

Irrigation: In a previous study assessing agricultural fields in Hangzhou Bay, they found out that the irrigation water brings plastic particles into the field (26). Microplastics enter agricultural soils using contaminated irrigation water, especially in areas where surface water is discharged into the environment from urban and industrial activities (26).

In general, agriculture has several direct and indirect sources of microplastic pollution. Although plastic mulches are the most prevalent, more evidence shows there are other important long-term inputs such as biosolids, compost and irrigation water. The importance of each source varies between regions depending on local agricultural status, climate and waste management systems.

Impact of microplastics on soil physical properties

Soil physical properties are among the most sensitive measures of soil health as they affect water movement, aeration, root penetration and soil structure. These properties can be altered by microplastics due to changes in particle arrangement, pore distribution and aggregate stability. However, the magnitude and direction of these effects depend on polymer type, particle shape, concentration and soil characteristics.

Soil texture

Soil texture is a key agroecological characteristic that is not affected by the presence of microplastic pollution (27). Most studies have found a negligible effect on soil texture, since the presence of microplastics affects soil structure but not the mineral particle-size distribution (27, 28). Soil texture is relatively stable after the addition of microplastics, but there may be indirect effects on other physical properties such as aggregation and porosity.

Soil porosity and bulk density

Soil is described as a porous material that contains both micro and macro pores (29). Soil porosity is a good indicator of soil health. Limited recent literature suggests that microplastic pollution resulting from human interventions affects the soil pore structure (30). Both increases and decreases in soil porosity have been reported in studies based on the characteristics of the microplastic as well as soil conditions. Specifically, Bulk density is also one of the key aspects of soil health to affect water and solute flow, enhance air diffusion in the soil and controls compaction of the soil. Several works admit that microplastic pollution tends to cause a reduction in the bulk density (31–33). The decrease in bulk density is mainly due to the shape, size and density of the microplastic particles added to soil (34).

All these results suggest that fibrous microplastics tend to increase pore connectivity and to decrease bulk density, while fragment- and film-shaped particles could block pores. Consequently, the variability of the observations between the studies is not due to contradictory mechanisms, but to differences in polymer characteristics, soil texture and experimental conditions.

Soil aggregation and structure

The mineral ions, organic compounds and pores in the soil coagulate and align in specific ways to form soil structure and this aggregation is useful in assessing the soil health (35, 36). The microplastics such as low-density polyethylene (LDPE) and polyamides in soil affect its aggregate size (37).

Soil water retention capacity

The impact of microplastic on soil water holding capacity varies according to different studies. Fibrous polymers typically increase the water retention of soil by improving pore connectivity, while fragment or film-shaped particles can decrease water retention by interfering with soil aggregation and changing the pore distribution (27). Therefore, the variance between studies is mostly related to the variations in the polymer type, particle morphology, soil texture and concentration of microplastics (34). Therefore, water-holding capacity should be interpreted together with other soil physical indicators rather than as an independent response to microplastic contamination.

Soil organic matter

Soil organic matter is fundamental for maintaining soil fertility, microbial activity and long-term ecosystem stability (38, 39). Microplastics made of polypropylene have the potential to alter nutrient dynamics through their effects on microbial activity and organic matter decomposition in soil (40). The amounts of soil organic matter in a particular soil type depends on the decomposer microorganisms and the degree of decomposition (41–43). A decrease in the soil microbial population could result in less breakdown of organic matter, affecting carbon cycling and nutrient

availability in agricultural soils. For instance, it is eloquently clear that microbes that contribute to the fixation of carbon dioxide and organic matter as components of soil, like Chlorofexi, reduce abundance after microplastic pollution (44, 45). The effects of microplastics on soil organic matter are generally related to the interaction of changes in microbial activity and soil physical structure. Long-term field experiments are needed to assess whether such effects are ultimately positive or negative to soil carbon storage in agriculture (Table 1).

Impact of microplastics on chemical properties of soil

The chemical characteristics of soil are significant factors for soil fertility due to their effect on soil nutrient availability, soil contaminant mobility, microbial activity and crop productivity. These properties can be directly affected by micro-plastic contamination due to particle interactions with the soil, or indirectly because on the decomposition of organic matter and microbial processes. However, the extent of these changes depends on polymer composition, weathering, exposure duration and soil characteristics.

Soil pH

Soil pH changes resulting from microplastic pollution have been reported in numerous studies, but the magnitude and direction of the changes depend on the polymer type, soil characteristics and time of exposure (47). For instance, when soil is exposed to a mixture of microplastics, the soil pH rises (48). On the other end of the soil pH, there indicated that it reduces after 30 days of contact with the high-density polyethylene (49). The changes in soil pH after microplastic contamination of soil, a decrease in pH has been observed from the use of aliphatic polyesters due to the formation of cracks in its surface in a process of mineralisation that lowers the soil pH (50–52). Soil microplastic contamination affects the pH of the soil due to disturbance of the specific microbes that release hydrogen cations. Phenanthrene is a polycyclic aromatic hydrocarbon (PAH) that can be adsorbed onto the surfaces of microplastics and thus impact soil microbial communities and nitrogen-transforming microorganisms (53).

Cation exchange capacity

The cation exchange capacity (CEC) is another soil attribute that describes the capability of the soil to supply nutrient cations, including calcium, magnesium and potassium available to plant uptake and it also helps to calculate the overall negative charge in the soil that retains plant nutrients (54). A decrease in CEC will have a negative effect on the availability and retention of essential soil nutrients, which in turn will have a negative impact on soil fertility in the long term if it is polluted with prolonged microplastic contamination (48). While there is limited evidence, recent studies indicate that the changing pH and organic matter of soils is the most important way that microplastics are likely to affect CEC.

Table 1. Alterations in soil physical properties due to microplastics

Sl. No.	Microplastic variety	Physical characteristics	Alterations	Conc.	Sources
1	PVC	Soil texture	Neutral	1.0	(28)
2	Polyester	Bulk density	Decrease	0.2	(32)
3	Polystyrene, Polyester	Soil Structure	Increase	2.0 each	(32)
4	PET	Water holding capacity	Increase	0.4	(45)
5	Polyethylene, Polystyrene	Organic matter	Decrease	0.2 and 2.0	(46)

PVC: polyvinyl chloride; PET: polyethylene terephthalate; Conc.: concentration.

Soil electrical conductivity

The electrical conductivity of soil has been applied in the assessment of soil quality regarding crop management practices (55, 56). Several of the most recent works have noted that exposure of the soil to 1.0 % LDPE does not affect the electrical conductivity of the soil. On the other hand, 2.0 and 10.0 % LDPE microplastics modified the soil without affecting the electrical conductivity (48, 57). The effect of microplastics on soil electrical conductivity seems to be mostly dependent on the level of contamination, polymer properties and soil composition. Further long-term studies under field conditions are required to better understand these responses. The major changes in soil chemical properties caused by different microplastics are summarised in Table 2.

Impact of microplastics on the biological properties of soil

Soil biological properties are sensitive indicators of soil health as they control nutrient cycling, organic matter breakdown, soil fertility and ecosystem function. Microplastic contamination can directly affect these biological processes by affecting soil organisms and indirectly by altering soil physical and chemical properties. As a result, changes in biological indicators can serve as a preliminary indicator of soil degradation under the influence of micro-plastics.

Organic carbon and nitrogen mineralisation

Mineralisation of organic carbon and nitrogen plays a critical role in the management of soils and crop production (50, 60). Low-density polyethylene and other polymer types have been reported to affect carbon and nitrogen mineralisation at concentrations between 0.1 % to 18 % in several studies. The responses are dependent of the concentration of micro-plastics, the polymer type and their effects on microbial activity in soil (60–62). According to earlier reports, microplastics in the soil can change the rate of carbon mineralisation in three ways: self-limiting reserved plant growth and magnitude of litter decay, regulating microbial activities in the soil and serving as a refractory carbon pool (61). The LDPE soil contamination affects soil mineralisation by enhancing the richness of microbial genes such as the nitrogenase reductase gene that facilitates fixation of nitrogen (62).

Soil enzyme activity

Soil enzymes are widely recognised as sensitive biological indicators because they regulate nutrient cycling, organic matter decomposition and overall soil functioning (63). Soil microplastic pollution can also alter enzyme activities. This can be in line with the

fact that some of the microplastics in the soil may be altering the soil's nutritional substrates and physicochemical properties, or these soil enzymes may be interacting with microplastic surfaces (64).

Soil respiration

Soil respiration is a biological factor that should be considered while determining the status of the soil (65, 66). The addition of microplastics such as polyethylene to the soil results in a reduction in soil respiration (45). The measured decrease in soil respiration is typically linked to the decrease of microbial activity and the suppression of enzyme function and changes in soil pore properties due to microplastic contamination (64).

Most of the existing data on the impacts of microplastic on soil health are from lab experiments under controlled conditions and high microplastic concentrations. While these studies offer insights into the mechanisms, they may not accurately reflect field conditions where distribution of microplastics, field interactions and exposure duration are more complex. Consequently, results of lab studies need to be treated with caution and more attention should be given to long-term field trials to formulate management recommendations for sustainable agricultural systems. The reported effects of microplastics on soil biological properties are summarised in Table 3.

Strategies for mitigation

Approaches to the eradication and control of microplastic pollution are needed to answer growing questions about land and sea environments. This is the core approach to addressing environmental issues since a reduction of the total production of plastics is promoted right from the source. Therefore, industries and consumers decrease plastic products from their source (70). Encouraging the use of biodegradable material, encouraging fewer use and disposal attitudes towards plastics and implementing environmentally friendly manufacturing processes can go a long way in mitigating the effects of plastic pollution on the environment. Adopt or apply measures that cap or ban Single-use production and consumption. Implement awareness programs to explain the effects of microplastic and improper use of plastics and encourage proper disposal of plastics and proper disposal of waste (71).

In agriculture

The recommended control measures for farmlands to reduce and prevent microplastic pollution are provided below:

Table 2. Changes in chemical properties of soil by microplastics

Sl. No.	Microplastic variety	chemical characteristics	Alterations	Conc.	References
1	PET	pH	Increase	5.0	(58)
2	Polyethylene	CEC	Decrease	10.0	(59)
3	LDPE	EC	No change	2 and 10	(48, 57)
4	LDPE	EC	decrease	1.0	(48)

PET: polyethylene terephthalate; CEC: cation exchange capacity; LDPE: low-density polyethylene; EC: electrical conductivity; Conc.: concentration.

Table 3. Changes in Biological properties of soil by microplastics

Sl. No.	Microplastic variety	Biological characteristics	Alterations	Conc.	References
1	Polyethylene	Carbon Mineralisation	Increase	0.1, 0.5, 1.0	(43)
2	Polyethylene	Soil respiration	Decrease	0.4	(67)
3	LDPE	Soil respiration	Increase	1.0	(68)
4	PVC, Polyethylene	Enzyme activity	Increase	1.0 and 5.0	(69)

LDPE: low-density polyethylene; PVC: polyvinyl chloride.

- Promoting the use of natural mulching substances, including residues, compost, or leaves instead of plastic mulch in horticulture for better enhancement of water retention, control of weeds as well as natural decomposition, to reduce plastics that are most likely to pollute the environment with micro-plastics (72).
- Reducing the overuse of coated fertiliser includes measures aimed at rationing and controlling the utilisation of this particular type of coated fertiliser (73). The implementation of various technologies like precision application to improve the competitiveness of agriculture, lessen negative environmental effects and promote sustainable farming (70).
- Now, the irrigation channels are made of foldable pipes, plastic conduits and plastic tubes and since some particles could be washed away during irrigation it may cause microplastic pollution. Therefore, an option like concrete and biodegradable pipes can be utilised in irrigation (74).
- There are enormous opportunities for using nanotechnology in agriculture (75). Effective partnerships with policymakers, researchers and other agricultural practitioners will help ensure that the best practices in the use of nanotechnology in addressing the problems of microplastics in the growing regions are achieved. Nanoencapsulation ensures a hail-safe and target delivery of allied inputs and unloads the possibility of microplastic pollution in soil and water bodies (76).
- Size and design nano sensors that would detect microplastic pollution in water or soil and these technologies provide trainable information to the farmer aiding him in determining the effectiveness of control strategies and adjusting accordingly. Nano-catalysts enhance the complete degradation of the residual plastics with progressive mitigation of the impacts of microplastics in regions of agricultural value.

Conclusion

Microplastic pollution in soil poses environmental indifference since it affects soil health in several physical, chemical and biological ways. There are several sources, like agriculture, urban-supplied water, effluence, septic sludge and compost. Microplastics significantly influence the soil's physico-chemical and biological attributes. However, there are many things unknown about these effects, such as the long-term consequences, how they interact with heavy metals and the effect on other linked ecosystems. Measures for the control include reducing the use of plastics, substituting those with biodegradable options and enhancing other garbage disposal measures. More work should be done to explore more information about this specific connection and how we can meet all the soil plus agriculture demands positively in the long run.

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Authors' contributions

DM contributed to conceptualisation, visualisation, resource provision and writing of the original draft, as well as review and editing of the manuscript. MSLR contributed to conceptualisation, methodology, data curation, formal analysis, validation, supervision and writing through review and editing. MMK, RS, NK and LR contributed to validation and supervision. MA, MRK, RRS, YAK and KM contributed to writing through review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

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