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RESEARCH ARTICLE

Physicochemical and nutrient status of agricultural soils in Southern Telangana Zone, India

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Abstract

A comprehensive assessment of soil fertility status was conducted across the Southern Telangana agro-climatic zone to evaluate key physicochemical and nutrient characteristics in agricultural soils. Soil samples (n = 125) were collected from paddy and maize cultivated agricultural fields and were analysed. The soil pH varied between 6.48 and 8.34, reflecting conditions that range from neutral to moderately alkaline, which are generally conducive to successful crop cultivation. Electrical conductivity remained low (mean EC = 0.24dSm^{-1}), suggesting minimal salinity constraints. Nutrient analysis revealed nitrogen deficiency in 73.6 % of samples, despite a wide range (75-401 kg ha^{-1}), indicating a critical need for nitrogen management. In contrast, phosphorus and potassium were found in sufficient to high levels in 81.6 % and 56.8 % of samples respectively, due to likely fertiliser accumulation and soil mineralogy. Organic carbon was generally low, with a mean of 0.5 % and 52 % of samples fell in the deficient category, highlighting the need for organic matter enhancement. Among micronutrients, iron was adequate in all samples, while 23 % of samples were deficient in zinc, pointing to a potential need for Zn supplementation. The results highlight the need for tailored and comprehensive nutrient management approaches to ensure consistent agricultural productivity and maintain soil health in the area.

Keywords: agricultural soils; micronutrients; nutrient status; physico-chemical properties; soil fertility

Introduction

As a key component of sustainable land use, soil delivers numerous critical ecosystem services that have a direct impact on both agricultural output and human quality of life (1-3). The preservation and enhancement of soil health have become globally critical, particularly in the context of declining soil quality, increasing demands for food security. The urgency was further intensified by mounting environmental challenges and the accelerating impacts of climate change (4, 5). Prolonged periods of drought, interspersed with episodes of intense rainfall, have been shown to exacerbate soil degradation processes, often leading to severe and in some cases, irreversible depletion of soil resources worldwide (6).

In semi-arid regions such as Telangana, India, soil fertility plays a pivotal role in determining agricultural productivity (7, 8). However, the region faces significant challenges due to climatic variability, continuous cultivation, insufficient nutrient management and prolonged application of inorganic fertilisers, all of which have contributed to the progressive deterioration of soil quality (9, 10). Assessing the physico-chemical and nutrient status of soils is therefore crucial for identifying localised fertility constraints and for developing effective, site-specific soil management strategies. Along with the concentrations of key macro- and micronutrients-especially nitrogen (N), phosphorus (P), potassium (K), iron (Fe) and zinc (Zn)- act as critical benchmarks in designing effective and sustainable nutrient management strategies and fundamental soil characteristics like pH, electrical conductivity (EC), organic carbon (OC) are also crucial (11-13).

In the Indian context and especially in Telangana, soil health has been further compromised by declining organic matter levels, nutrient mining due to continuous cropping, imbalanced fertiliser application and limited awareness of micronutrient deficiencies (14, 15). Consequently, crop production has plateaued in numerous regions despite higher input application. This underscores the critical necessity for data-driven evaluations of soil fertility and the implementation of integrated nutrient management (INM) approaches to promote long-term sustainable agriculture.

The Southern Telangana Zone (STZ) stands out as an important agricultural region within Telangana, known for its varied soil types, multiple cropping patterns and extensive cultivation of both staple and cash crops such as sorghum, cotton, maize, red gram, castor, safflower, sesame, groundnut and rice. However, there is a significant gap in localised information on soil nutrient levels and fertility challenges. Critical soil parameters such as OC, pH and EC, as well as the presence of essential nutrients (nitrogen, phosphorus, potassium, iron and zinc) need to be understood to pinpoint nutrient deficiencies and to guide sustainable management. The purpose of this research was to determine the current situation of these soil health indicators in the STZ. The insights are intended to improve integrated nutrient management, promote balanced fertiliser use and inform data-driven policies that will promote long-term agricultural sustainability in the region.

Materials and Methods

Study area

The STZ has the districts of Hyderabad, Medchal-Malkajgiri, Vikarabad, Yadadri-Bhuvanagiri, Rangareddy, Jogulamba-Gadwal, Nalgonda, Suryapet, Wanaparthy, Nagarkurnool and Mahabubnagar. Agriculture is important here and the semi-arid climate brings about 606 mm to 853 mm of rain every year, mainly during the southwest monsoon. In this area, the temperature changes a lot, with the highest being 28 °C to 38 °C and the lowest between 16 °C and 25 °C during the growing season. It is also notable that there are many types of soil in the STZ. There are 19 types of soil in the region and the biggest area is covered by red clayey soils (22.3 %), then red gravelly loam (16.5 %) and alluvio-colluvial soils (14.4 %). The area has mainly red soils, which account for about 54.8 % of the land. There are also 11.2 % of the land in the area that has alluvio-colluvial and calcareous soils.

Soil sampling and soil characterisation

A total of 125 surface soil samples were collected from paddy and maize growing fields in the STZ using a stratified sampling approach, targeting the 0-15 cm topsoil layer. The study area and sampling locations are shown in Fig. 1. The samples were shade-dried, ground manually using a pestle and mortar, passed through a 2 mm sieve and stored in labelled containers for further laboratory evaluation. Soil pH was measured using a glass electrode pH meter in a 1:2.5 soil: water ratio suspension. EC was assessed in the same extract using a digital conductivity meter (16). OC was determined following the wet oxidation method (17). Available nitrogen was estimated using the alkaline potassium permanganate technique (18). Phosphorus availability was evaluated by extracting soil with Olsen's reagent and measuring absorbance at 660 nm with a colourimeter, using ascorbic acid as the reducing agent (19, 20). Exchangeable potassium was with neutral normal ammonium acetate and quantified using a flame photometer, following standard procedures (16). Micronutrients were extracted using diethylene triamine pentaacetic acid (DTPA) and analysed through atomic absorption spectrophotometry using a Varian AAS 420 (21).

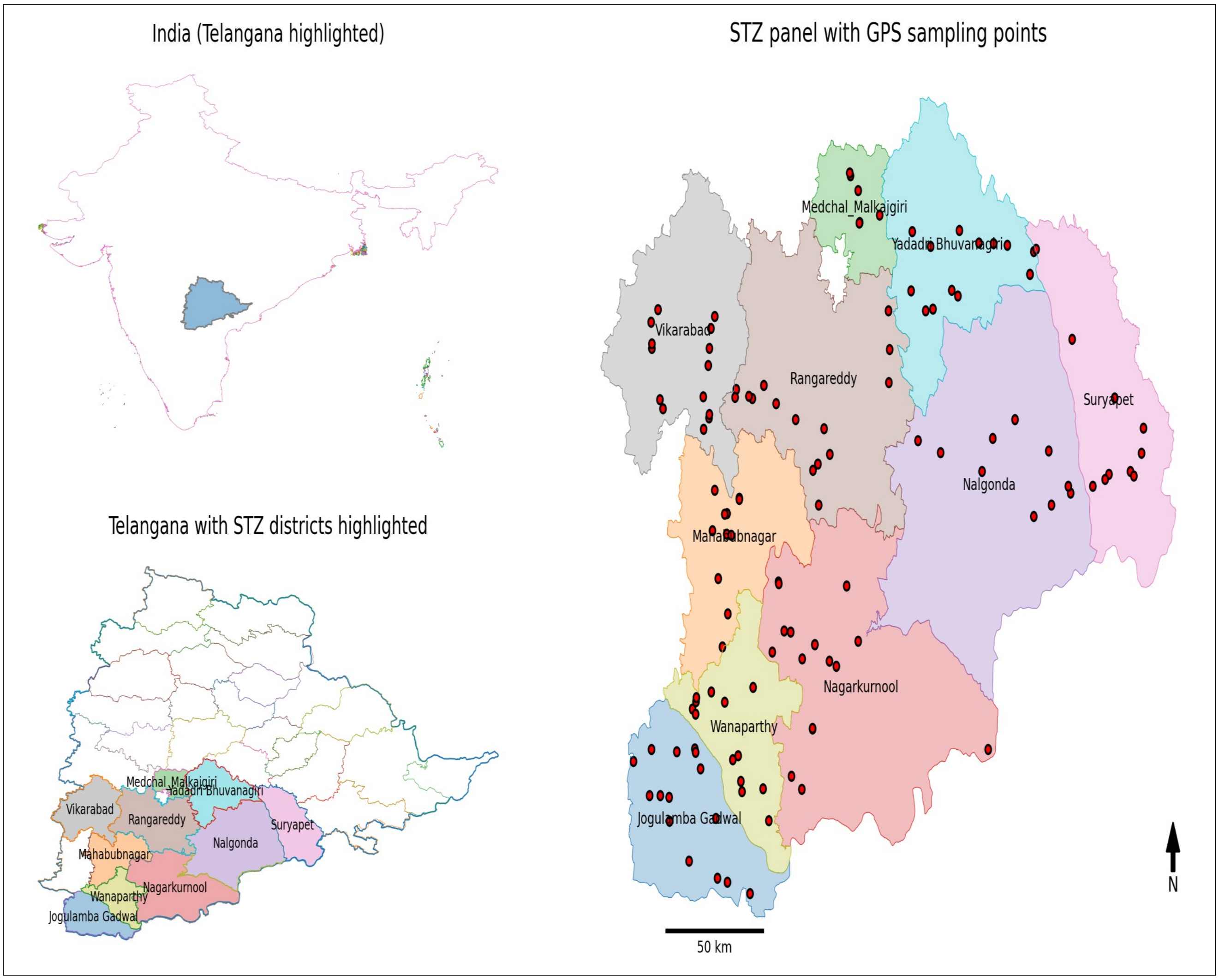

Fig. 1. Study area and mapping of soil sampling locations in the Southern Telangana Zone.

Results and Discussion

A comprehensive soil analysis conducted across the STZ revealed considerable spatial variability in both physicochemical and chemical soil properties, which are summarised in Table 1, with important implications for nutrient management and sustainable crop production in this semi-arid region. The findings on soil pH and EC are particularly valuable for guiding agricultural practices and improving crop yields in the region. Among the physicochemical attributes, soil pH emerged as a key indicator influencing nutrient solubility and overall soil fertility. The observed pH range of 6.48 to 8.34 showed that the soils are neutral to moderately alkaline, which is generally conducive to nutrient availability and uptake. This range reflects the cumulative effect of acid-base reactions within the soil matrix and supports the cultivation of a wide variety of crops, ensuring flexibility for farmers in crop selection and rotation. Furthermore, EC values remained low, ranging between 0.02 and 0.77 dS m^{-1}, with an average value of 0.24 dS m^{-1}, showing the negligible salinity-related constraints. This is a crucial finding, as low salinity enhances root development, water absorption and nutrient efficiency, all of which contribute to healthier plant growth and improved yields (22, 23).

The findings on soil OC reveal a critical area for improvement in sustaining and enhancing soil fertility across the region. OC ranged from 0.10 to 1.54 with an average of 0.5 %, which is indicative of overall low organic matter in the soils. The analysis of the OC content demonstrated that 52 % of the samples were in the low category, 28 % in the medium and 20 in the high, underscoring a widespread deficiency in organic matter (Fig. 2). Low OC content has direct implications for soil productivity, as it affects soil structure, water retention, microbial activity and nutrient availability- all of which are essential for optimal crop growth. This highlights the need for enhanced organic matter management, such as the application of farmyard manure, compost and the incorporation of green manure crops, to improve soil structure, microbial activity, soil fertility and nutrient cycling (24, 25).

Table 1. Physico-chemical characterisation of soils (N=125) in the Southern Telangana agro-climatic zone

Parameter	Range	Mean
pH	6.48 – 8.34	7.36
EC (dS m^{-1})	0.02 – 0.77	0.24
OC (%)	0.10 – 1.54	0.51

Enhancing OC levels can significantly boost soil health, promote better root development and increase nutrient-use efficiency, ultimately leading to higher and more sustainable crop yields. For farmers, investing in organic amendments offers a long-term solution to maintaining productive soils and adapting to changing climatic and agronomic conditions. Spatial heterogeneity of nutrient status was observed between the soils considered in the current study area, particularly in the case of available nitrogen (Table 2). The range of the available nitrogen content was 75-401 kg ha^{-1} with an average of 240.29 kg ha^{-1}. Regardless of this variation, 73.6 % of the samples were classified as nitrogen-deficient. Indicates that nitrogen (N) is the most limiting nutrient in the region's soils. This widespread deficiency is a critical concern for agricultural productivity, as nitrogen plays a central role in plant growth, chlorophyll synthesis and biomass accumulation.

Research indicates that tropical soils are prone to nitrogen depletion due to high rates of mineralisation, leaching and volatilisation under semi-arid conditions (26-28). In the context of Telangana, low nitrogen availability has been linked to intensive cropping, insufficient organic matter inputs and elevated temperatures that exacerbate nitrogen losses through volatilisation and denitrification (29-31). These findings underscore the need for INM strategies that incorporate organic

Table 2. Soil nutrient status (n=125) in the Southern Telangana agro -climatic zone

Nutrient	Range	Mean (kg ha^{-1}/ mg kg^{-1})
Nitrogen (N)	75 – 401 kg ha^{-1}	240.29 kg ha^{-1}
Phosphorus (P_2O_5)	20 – 111 kg ha^{-1}	75.36 kg ha^{-1}
Potassium (K_2O)	60 – 842 kg ha^{-1}	346.73 kg ha^{-1}
Iron (Fe)	4 – 43.20 mg kg^{-1}	23.51 mg kg^{-1}
Zinc (Zn)	0.29 – 4.14 mg kg^{-1}	1.41 mg kg^{-1}

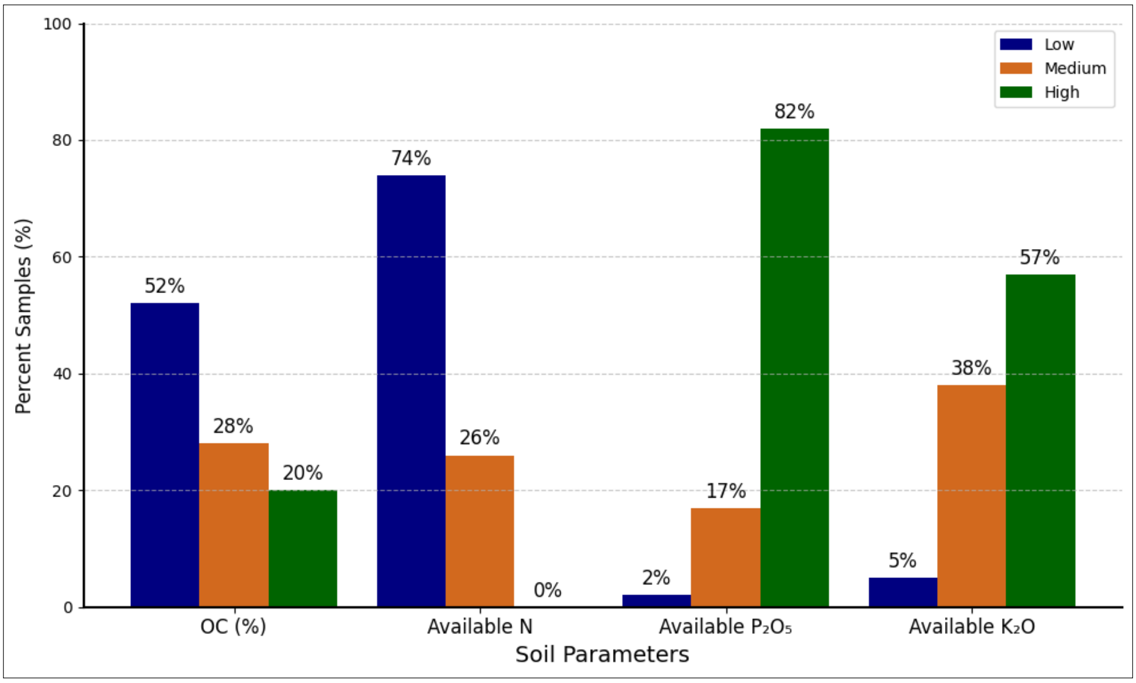

Fig. 2. Percent distribution of soil samples by low, medium and high NPK and organic carbon levels in STZ.

inputs, legume rotations and judicious use of nitrogen fertilisers to replenish nitrogen levels and sustain crop yields.

Conversely, phosphorus (P) availability was found to be adequate in the majority of samples, with 81.6 % of soils categorised as high in available phosphorus, which could be the consequence of previous fertilisation activities or natural fertility of the soil. The concentrations of available phosphorus (P_2O_5) were between 20 and 111 kg ha^{-1} with a mean of 75.36 kg ha^{-1}. This is likely the result of long-term and excessive application of phosphatic fertilisers, leading to P accumulation in the surface layers (32). Additionally, the immobile nature of phosphorus in soil, which leads to its confinement to the rhizosphere, contributes to its accumulation in surface horizons (33). Consistent findings have been reported in other parts of India, including Amritsar (Punjab), Haveri (Karnataka) and Coimbatore (Tamil Nadu), during soil fertility mapping efforts (34, 35). Research indicates that significant phosphorus buildup was noticed due to continuous P fertilisation in Indian soils (36).

While high phosphorus levels may reduce immediate fertilisation needs, they also highlight the importance of balanced nutrient management to prevent environmental issues such as eutrophication and phosphorus lock-up, where excess P becomes unavailable to plants due to fixation. The potassium (K_2O) levels were also found to be generally sufficient, with a significant range of 60 to 842 kg $ha^{-1,}$ which translates to an average of 346.73 kg ha^{-1}. With fertility ratings, the samples were found to fall in high potassium category (56.8 %), medium category (38 %) and low category (6 %) indicating that potassium availability is mostly adequate to high across most of the region (Fig. 2). This may be ascribed to the mineral composition of the parent material, as well as limited crop removal and contributions from organic residue decomposition, potassium fertilizers and upward capillary movement of K-rich groundwater (37). These results suggest that potassium may not be a limiting factor in most areas, but localised deficiencies still require monitoring, especially under intensive cropping or sandy soil conditions.

Micronutrient analysis indicated a contrasting pattern between Fe and Zn availability in the soils of the STZ (Table 2 and Fig. 3). Fe levels were found to be sufficient in the tested soil samples, ranging from 4.20 mg kg^{-1} to 43.20 mg kg^{-1}, with a mean of 23.5 mg kg^{-1}. All the samples fell within the sufficiency level, implying that there were no Fe-related constraints to crop growth. This ensures that critical physiological functions supported by iron—such as chlorophyll synthesis and enzyme activation—are well-maintained in the soils studied. On the other hand, the levels of Zn were more variable, with a range of 0.29 mg kg^{-1} to 4.14 mg kg^{-1} with a mean of 1.41 mg kg^{-1}. The percentage of adequacy of Zn in the samples was approximately 77 % and 23 % deficient. The current research study supports the fact that Zn supplementation at the regional level in soils with deficiency can improve the nutrient delivery and crop performance and final yield results. Zn deficiency has been commonly associated with the prolonged cultivation of high-yielding varieties (HYVs), especially rice and wheat, without adequate crop rotation or micronutrient replenishment and may be attributed to elevated pH levels, which promote the formation of insoluble zinc compounds, thereby limiting its solubility and plant uptake (38, 39). Moreover, excessive application of phosphatic fertilisers can suppress zinc bioavailability due to antagonistic interactions in the soil (15).

Given these findings, targeted zinc supplementation-particularly in identified deficient zones- can significantly improve nutrient delivery, plant vigour and final crop yields. This reinforces the need for micronutrient-based soil testing and localised fertiliser recommendations, ensuring balanced nutrition and long-term soil health. The combined analysis shows a significant physicochemical heterogeneity in the STZ, especially in terms of OC, pH and major nutrient levels. Most of the profiles record medium to low OC, although pH values are generally consistent with agronomic optima. The most evident limitation is nitrogen in most of the analysed samples and the concentration of phosphorus and potassium is satisfactory or even high. The micronutrient status is unevenly distributed, with iron being sufficient and zinc deficiency being evident in about 23 % of the samples. These findings, therefore, provide an important empirical basis for justifying soil fertility

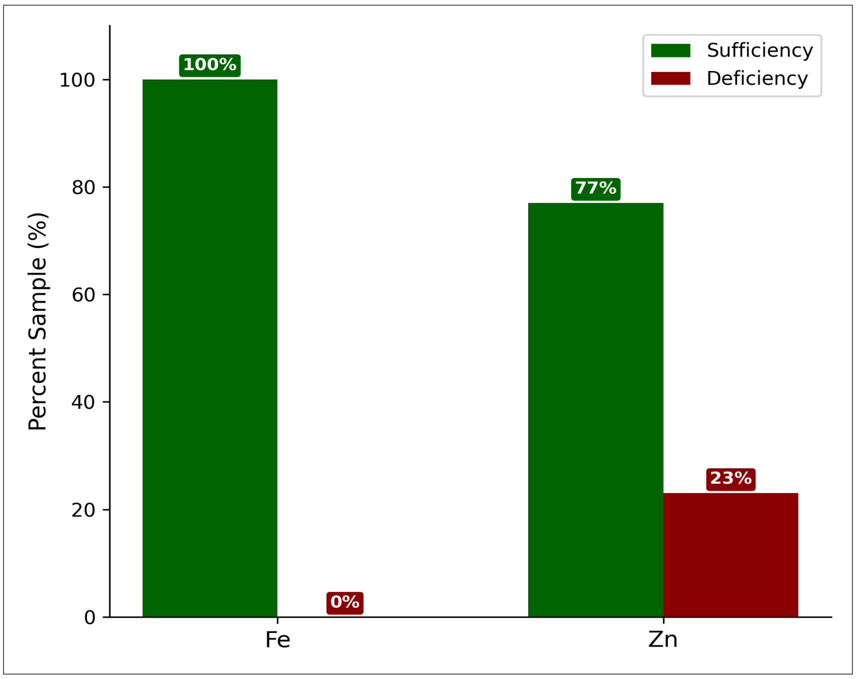

Fig. 3. Percent distribution of soil samples showing Fe and Zn sufficiency and deficiency in STZ.

interventions and the need to foster sustainable crop production in the Southern Telangana Agro-climatic Zone.

Implications for farmer practices and policy interventions

The findings provide clear direction for improving soil fertility management in the STZ. At the farm level, the widespread nitrogen deficiency and low OC highlight the need for INM-combining chemical fertilisers with organic inputs like compost, green manure and crop residues. Meanwhile, the generally adequate levels of phosphorus and potassium suggest the need for balanced fertilisation, avoiding unnecessary applications. The observed zinc deficiency (in ~ 23 % of samples) indicates the need for targeted micronutrient supplementation, such as zinc-enriched fertilisers or foliar sprays. For policymakers, the results support region-specific fertiliser recommendations, soil health card-based interventions and incentives for soil testing and organic input use. Strengthening extension services and promoting awareness programs can help scale sustainable nutrient management and improve crop productivity across the zone.

Conclusion

Nitrogen Deficiency is Widespread: Over 73 % of soil samples were nitrogen-deficient, identifying nitrogen as the most limiting nutrient for crop growth in the region. This calls for the immediate adoption of INM strategies. Low OC undermines soil health: more than half of the soils showed low organic carbon levels, emphasising the need for increased organic matter inputs such as compost, green manure and crop residues. Phosphorus and Potassium are generally sufficient: Most samples had adequate to high levels of phosphorus and potassium, suggesting that site-specific fertilisation can help avoid excessive and unnecessary application of these nutrients. Micronutrient imbalances exist: while iron levels were sufficient across all samples, about 23 % showed zinc deficiency, indicating a need for targeted zinc supplementation to ensure balanced micronutrient nutrition.

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Authors' contributions

This work was carried out in collaboration among all authors. DR prepared the research paper. PSB and AM conceptualised, provided guidance and direct supervision, including responsibility for the original draft. TR, KPV and MS were extensively involved in experimental administration, supervision, formal analysis, as well as editing and finalising the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

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

Ethical issues: None

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