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Senna italica as an Ecosystem Engineer: Enhancing Soil Fertility and Function in Nutrient-Poor Sandy Soils

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Arid and semi-arid soils are typically characterised by low fertility, limited nutrient availability, and weak structural stability, posing major challenges for sustainable land management. Native plant species that naturally improve soil quality may provide environmentally sustainable solutions for restoring degraded sandy ecosystems. This study evaluated the influence of *Senna italica*, a native leguminous shrub, on the physicochemical properties and fertility of nutrient-poor sandy soils in Jeddah, Saudi Arabia. Soil samples were collected beneath naturally established *S. italica* plants and from adjacent non-vegetated areas for comparison. Soil texture, pH, electrical conductivity (EC), and available nitrogen (N), phosphorus (P), and potassium (K) were determined, and root samples were stained and examined for arbuscular mycorrhizal fungal (AMF) colonisation. Although both soils were classified as sandy, soils beneath *S. italica* contained a greater proportion of fine particles (4.20% vs. 2.12% silt + clay). Rhizosphere soils exhibited significantly lower pH and significantly greater concentrations of available N, P, and K than adjacent non-vegetated soils,

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whereas EC did not differ significantly. Microscopic observations confirmed extensive AMF colonisation of *S. italica* roots, including hyphae and vesicles. These findings suggest that *S. italica* enhances soil fertility through integrated plant–soil–microbe interactions involving biological nitrogen fixation, rhizosphere-mediated nutrient mobilisation, and mycorrhizal associations. The study identifies *S. italica* as a potential ecosystem engineer with promising applications in ecological restoration, soil rehabilitation, and sustainable management of degraded sandy soils in arid and semi-arid regions.

Keywords: Senna italica; arid ecosystems; ecosystem engineering; plant–soil–microbe interactions; sandy soils; soil fertility; nutrient cycling; rhizosphere acidification; arbuscular mycorrhizal fungi; ecological restoration.

1. Introduction

Arid and semi-arid regions are characterised by harsh environmental conditions that severely limit soil fertility. These constraints arise from extreme temperature fluctuations coupled with limited water availability. In general, soils in these regions are inherently low in fertility, exhibiting low concentrations of essential nutrients such as nitrogen and phosphorus, limited water-holding capacity, alkaline pH, and minimal soil organic matter. Hence, maintaining and improving soil fertility in these fragile environments is a critical global challenge. Thus, developing long-term soil fertility management strategies that are both productive and environmentally sustainable remains an ongoing challenge.

Saudi Arabia is characterised by an arid to semi-arid climate, with low and erratic rainfall, high temperatures, and intense evaporation. Consequently, its soils are predominantly sandy, alkaline, low in organic matter and essential nutrients, and have limited water-holding capacity (Al-Ghamdi et al., 2021). Therefore, detailed soil characterisation and the use of site-specific soil information are essential for improving soil fertility, informing appropriate management practices, and supporting sustainable agricultural production. In addition, comparing soils associated with different vegetation types may provide valuable insights into the legacy effects of native plants on soil physical and chemical properties. Such knowledge could facilitate the identification of species that have the potential to serve as natural soil amendments or cover crops to enhance soil fertility in arid environments. Root–microbe interactions in the rhizosphere can alter local nutrient availability through exudation and mycorrhizal networks (Adal, 2023).

S. italica forms part of the natural vegetation of Saudi Arabia and is distributed mainly in arid and semi-arid environments, particularly in shallow wadis, sandy plains, and the lower slopes and foothills of mountainous areas (Filimban et al., 2014). It commonly grows in sandy or silty soils where water accumulates temporarily following rainfall. It is widely distributed across Africa, Asia, and parts of Europe (Chandran, 2015). It is also native to the Kingdom of Saudi Arabia, where it occurs extensively in several regions, including Jeddah (Aljedaani & Fakhry, 2023). The subspecies occurs from coastal areas at sea level to elevations of approximately 950 m, indicating its adaptation to a broad range of dryland habitats. Its tolerance of drought, high temperatures, and nutrient-poor soils enables it to persist in the harsh desert environments characteristic of many regions of Saudi Arabia. Thus, studying the soil beneath this plant may provide insights into its adaptation and the soil legacy it may create, which could support the establishment and growth of other plant species.

This plant belongs to the legume family, members of which are known for their nitrogen-fixing potential and arbuscular mycorrhizal associations; both attributes can positively affect soil microbial activity and nutrient availability. It is also rich in multiple phytochemicals, including norrubrofusarin gentiobioside, aloe-emodin glucoside, sennosides A and B, cassic acid (rhein) glucoside, rutin, de-methyl-toralactone hexoside, kaempferol-O-hexoside-pentoside, 2-hydroxyemodin glucoside, tinnevellin-O-glucoside, torachrysone/isotorachrysone O-glucoside, rhamnetin/isorhamnetin 3-neohesperidoside, nepetin di-hexoside, 2′,3′,4′,6,7-pentahydroxyflavone di-hexoside, as well as torachrysone, isotorachrysone, and tinnevellin (Towanou et al., 2023; Zibaee et al., 2023). Many of these secondary metabolites have been shown to influence soil microbial communities, regulate nutrient cycling, and contribute to organic matter decomposition, thereby affecting soil health and ecosystem functioning.

This multifunctional role of phytochemical-rich plants has stimulated growing interest in their agricultural applications. Numerous plant species with abundant bioactive compounds or nitrogen-fixing capabilities have been successfully used as cover crops, green manures, or soil amendments. These include legumes such as clover, hairy vetch, and cowpea, as well as non-leguminous species such as rye, oats, barley, mustard, buckwheat, and radish. These plants are widely recognised for improving soil fertility through biological nitrogen fixation, organic matter inputs, weed suppression, stimulation of microbial activity, and enhanced nutrient availability, thereby increasing the productivity of subsequent crops (Virk et al., 2021). Given its comparable functional traits, *Senna italica* may represent an overlooked candidate for sustainable soil management. In a semi-arid legume system, combined AMF-rhizobial inoculation improved several soil chemical properties relative to uninoculated controls (Mpongwana et al., 2024).

As a leguminous species, *S. italica* can contribute biologically fixed nitrogen to the soil, and its diverse phytochemical profile may further influence soil microbial communities and nutrient dynamics. Moreover, *S. italica* naturally hosts abundant arbuscular mycorrhizal fungi (AMF) (AlZain et al., 2020), which play a pivotal role in enhancing phosphorus acquisition, improving nutrient-use efficiency, promoting soil aggregation, and supporting overall soil fertility. Recent evidence also supports complementary rhizobial-AMF effects in legumes (Koffi et al., 2025), enhanced nutrient uptake under drought following mycorrhizal inoculation (Zaman et al., 2024), and context-dependent field responses to AMF (Lutz et al., 2023). Collectively, these attributes suggest that *S. italica* could be utilised as an ecosystem engineer and may have considerable potential as a cover crop or organic soil amendment for sustainable agriculture in arid and semi-arid environments. However, despite these promising characteristics, its influence on soil physicochemical properties, nutrient availability, and overall soil fertility remains largely unexplored, representing an important knowledge gap. Therefore, this study investigated the effects of *S. italica* on soil fertility and soil physical properties in coastal sandy soils of Jeddah by comparing soils collected beneath naturally established *S. italica* stands with adjacent non-vegetated soils. We hypothesised that *S. italica* acts as an ecosystem engineer by improving soil physicochemical properties and nutrient availability through plant-mediated rhizosphere modifications, thereby enhancing soil fertility in nutrient-poor sandy ecosystems.

2. Materials and Methods

2.1 Experimental Site

Two locations were selected in southern Jeddah: one was frequently covered by *S. italica* following rainy seasons, whereas the other was not.

2.2 Soil Characteristics

The physicochemical properties of the soil were determined by analysing soil texture, pH, EC, and plant-available macronutrients (N, P, and K). Soil texture was determined using the dry sieve analysis method to assess the distribution of coarse soil fractions. Briefly, a 500 g air-dried soil sample was weighed using an analytical balance and transferred to a stack of standard sieves arranged in descending order of mesh size (Table 1). The sieve stack was mounted on a mechanical sieve shaker and agitated for 10–15 min to separate soil particles according to size. Soil pH and EC were determined using a 1:5 (w/v) soil-to-water suspension. Briefly, 5 g of air-dried, sieved soil was mixed with 25 mL of distilled water, shaken for 10 min, and allowed to equilibrate for 30 min. The pH was measured with a calibrated digital pH meter, and EC was measured with a calibrated conductivity meter. Available nitrogen (N) was determined as extractable ammonium (NH_4^+) and nitrate (NO_3^-) after extraction with 2 M KCl, and the extracts were quantified by flow-injection spectrophotometry. Available phosphorus (P) was determined using the Olsen extraction method, in which 2.5 g of air-dried soil was extracted with 50 mL of 0.5 M $NaHCO_3$ (pH 8.5) for 30 min, filtered through Whatman No. 42 filter paper, and the phosphorus concentration in the extract was measured by inductively coupled plasma optical emission spectrometry (ICP-OES). Available potassium (K) was determined in the soil extract by ICP-OES. The analytical procedures were performed according to standard soil chemical analysis methods (Olsen, 1954; Sparks *et al.*, 2020).

2.3 Arbuscular Mycorrhizal Fungi (AMF) Staining and Colonisation Assessment

Root samples were thoroughly washed over a sieve under running tap water to remove adhering soil particles. Clean roots were cut into approximately 1 cm segments and transferred to test tubes. The root segments were cleared in 10% (w/v) KOH by heating at 90 °C for 15–30 min until the tissues became transparent. After clearing, the roots were rinsed several times with tap water to remove residual KOH. The samples were then acidified in 1% (v/v) HCl for 3–5 min at room temperature. Subsequently, the acidified roots were stained with 0.04% trypan blue prepared in lactoglycerol (lactic acid: glycerol:water, 1:1:1) and heated at 90 °C for 5–10 min.

Table 1. Standard sieve sizes used for dry sieve analysis of soil samples

Mesh size (mm)	Particle fraction retained
3.35	Very coarse gravel and coarse fragments
2.00	Fine gravel
0.50	Very coarse sand
0.15	Medium to coarse sand
0.125	Fine sand
0.075	Very fine sand
0.053	Silt-sized particles and fine residue
<0.053	Fine silt and clay fraction

After staining, excess stain was removed, and the roots were destained in lactoglycerol until background staining was reduced and fungal structures became clearly visible. The stained root samples were stored in lactoglycerol at 4 °C until further analysis. Stained root segments were mounted on slides and examined under a light microscope.

2.4 Statistical Analysis

Statistical analysis was performed using GraphPad Prism (version 11). Differences between soil beneath *Senna* and adjacent non-vegetated soil in EC, pH, and available N, P, and K were analysed using an unpaired (independent) Student's t-test. A p-value of less than 0.05 ($P < 0.05$) was considered statistically significant.

3. Results

Soils collected beneath *Senna italica* and from adjacent non-vegetated areas were classified as sandy using the USDA soil texture triangle. However, differences in particle-size distribution were observed between the two microsites (Table 2). Soil beneath *S. italica* contained 95.80% sand and 4.20% silt + clay, whereas soil from the adjacent non-vegetated area contained 97.88% sand and 2.12% silt + clay.

Table 2. Particle-size distribution and USDA textural classification of soils collected beneath *Senna italica* and adjacent unvegetated soil

Soil property	With *Senna italica*	Without *Senna italica*
Sand (%)	95.80	97.88
Silt + clay (%)	4.20	2.12
USDA textural class	Sand	Sand

Soil pH differed significantly between the two sampling locations (Fig. 1a). Soil beneath *S. italica* exhibited a significantly lower pH than soil collected from adjacent non-vegetated areas ($P < 0.001$). In contrast, although electrical conductivity (EC) was slightly higher beneath *S. italica*, the difference was not statistically significant (Fig. 1b; $P = 0.11$).

Available macronutrients were consistently higher in soils beneath *S. italica*. Available nitrogen was significantly higher beneath *S. italica* than in non-vegetated soil (Fig. 2a; $P = 0.03$). Similarly, available phosphorus (Fig. 2b; $P = 0.03$) and available potassium (Fig. 2c; $P = 0.04$) were significantly elevated beneath *S. italica*.

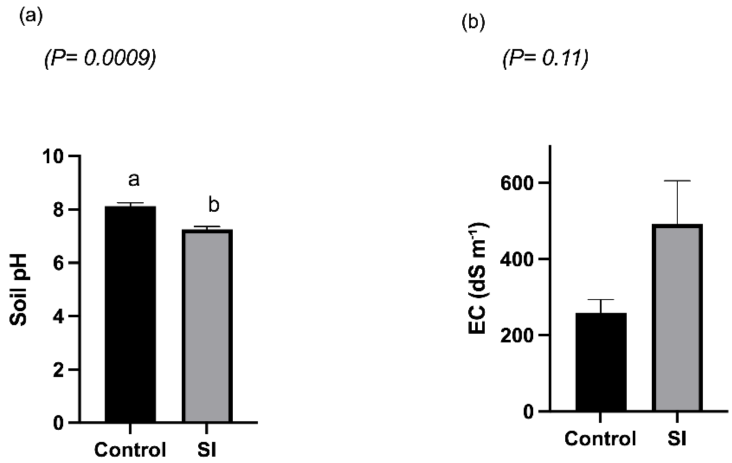

Fig. 1. Effects of *S. italica* vegetation (SI) on soil pH (a) and soil EC (b). Bars represent the pH and EC concentrations in soils collected beneath *S. italica* (SI) and adjacent unvegetated control (Control) sites. Bars represent the mean ± standard error (SE). Different lowercase letters above the bars indicate significant differences between treatments (*P* < 0.05)

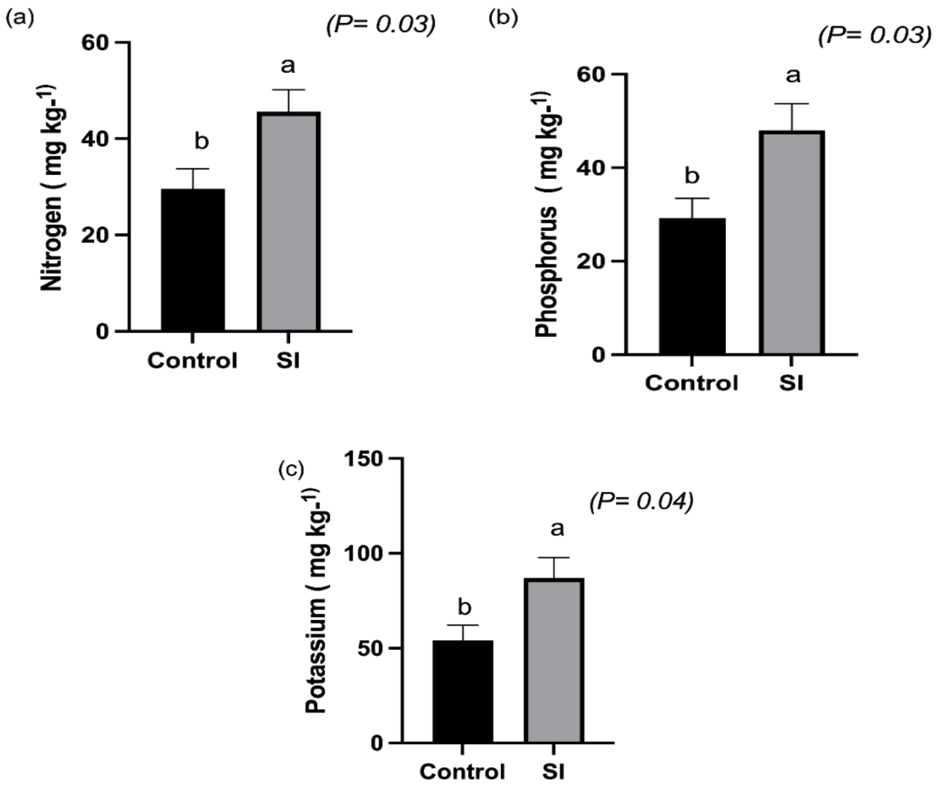

Fig. 2. Effects of *S. italica* vegetation on soil nutrient availability. Bars represent the concentrations of (a) available nitrogen (N), (b) phosphorus (P), and (c) potassium (K) in soils collected beneath *S. italica* (SI) and adjacent unvegetated control (Control) sites. Values are presented as mean ± standard error (SE). Different lowercase letters above bars indicate significant differences between treatments (*P* < 0.05) based on Student's *t*-test. Nutrient concentrations are expressed as mg kg^{-1} dry soil

Arbuscular mycorrhizal fungi (AMF) structures were observed in roots associated with *S. italica*, including hyphae, vesicles, and arbuscules (Fig. 3), confirming successful colonisation under field conditions.

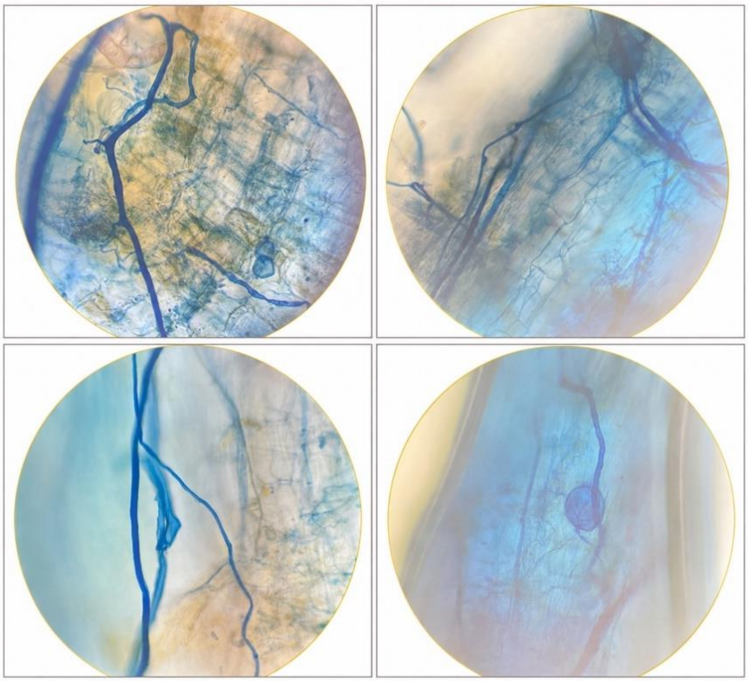

Fig. 3. Representative light micrographs of trypan blue-stained *Senna italica* roots showing arbuscular mycorrhizal fungi (AMF) colonization, with intraradical hyphae and a vesicle

4. Discussion

Although soils from both vegetated and non-vegetated sites were classified as sandy according to the USDA soil texture triangle, soils beneath *Senna italica* contained a greater proportion of fine particles (silt + clay). This relatively small increase is ecologically important because even modest enrichment of the fine fraction can substantially increase specific surface area and cation exchange capacity (CEC), thereby improving water retention and nutrient adsorption in coarse-textured soils. These changes are likely driven by plant-mediated pedogenic processes, including litter deposition, root turnover, rhizodeposition, and the formation of stable soil aggregates around the rhizosphere. Such modifications improve the physical environment for both plant roots and soil microorganisms and represent an early stage of soil development in nutrient-poor sandy ecosystems.

The significant reduction in soil pH beneath *S. italica* indicates active rhizosphere acidification. This process is likely mediated by proton (H^+) release during nutrient uptake, secretion of low-molecular-weight organic acids such as citrate, malate, and oxalate, and nitrification associated with biological nitrogen fixation (Shen et al., 2004). In alkaline, carbonate-rich soils typical of arid environments, localised acidification enhances nutrient availability by increasing the solubility of sparingly available minerals, particularly calcium-bound phosphorus (Ström et al., 2005).

In contrast, electrical conductivity was not significantly influenced by vegetation cover, suggesting that salinity remained largely controlled by inherent soil characteristics rather than by *S. italica*. The slight increase observed beneath the canopy may reflect localised accumulation of soluble ions released through litter decomposition and rhizosphere turnover, offset by plant uptake and natural leaching processes.

The significantly greater concentrations of available nitrogen, phosphorus, and potassium beneath *S. italica* demonstrate a strong positive plant–soil feedback that enhances nutrient cycling. Increased nitrogen availability is consistent with the well-established nitrogen-fixing capacity of legumes, in which rhizobial symbiosis converts atmospheric nitrogen into plant-available forms that subsequently enter the soil via root exudation, nodule senescence, and litter decomposition (Kumari & Maiti, 2022).

Enhanced phosphorus availability is likely attributable to complementary rhizosphere processes, including acidification that increases phosphorus solubility in alkaline soils (Li et al., 2024) and microbial production of organic acids and phosphatase enzymes that mobilise phosphorus from both mineral and organic pools. Organic acids (e.g., gluconic and citric acids) solubilise insoluble phosphate minerals through acidification and chelation of metal cations (Ca, Fe, and Al), whereas phosphatase enzymes hydrolyze organic phosphorus compounds into plant-available inorganic phosphate. Together, these processes increase phosphorus bioavailability and improve plant nutrient acquisition in nutrient-poor soils (Pang et al., 2024; Ramos Cabrera et al., 2024). Similarly, the increase in available potassium may result from enhanced mineral weathering promoted by rhizosphere acidification and microbial activity, together with improved nutrient retention associated with a greater proportion of fine particles and the accumulation of organic matter.

The observed colonisation of *S. italica* roots by arbuscular mycorrhizal fungi (AMF) suggests that mycorrhizal symbiosis represents an additional mechanism contributing to improved soil function. AMF extend the effective absorptive surface area of plant roots through extensive extraradical hyphal networks, thereby increasing access to relatively immobile nutrients, particularly phosphorus. Beyond nutrient acquisition, AMF promote soil aggregation through the production of glomalin-related soil proteins, which improve aggregate stability and contribute to greater nutrient and water retention (Zaman et al., 2025). The simultaneous occurrence of AMF colonisation and enhanced soil fertility indicates that plant–microbe interactions likely play an important role in sustaining nutrient cycling in these nutrient-deficient sandy soils.

Collectively, the results support the hypothesis that *S. italica* functions as an ecosystem engineer, modifying both the physical and chemical properties of nutrient-poor sandy soils. Through the integrated effects of litter inputs, rhizosphere acidification, biological nitrogen fixation, enhanced microbial activity, mycorrhizal associations, and aggregate formation, the species creates a more favourable soil environment that supports improved nutrient availability and soil functionality.

These integrated plant–soil–microbe interactions are particularly important in arid and semi-arid ecosystems, where biological processes often represent the primary drivers of soil development. By enhancing nutrient cycling, improving soil structure, and increasing resource retention, *S. italica* may facilitate the establishment of neighbouring vegetation and contribute to long-term ecosystem resilience. Consequently, this native legume shows considerable potential as a candidate species for ecological restoration, soil rehabilitation, and sustainable land management in degraded sandy landscapes.

5. Conclusions

The study indicates that *S. italica* is associated with measurable improvements in selected soil properties under sandy coastal conditions in Jeddah, Saudi Arabia. Soils beneath *S. italica* showed a slightly higher proportion of fine particles compared with adjacent non-vegetated soils, suggesting modest improvement in soil structural characteristics. The significant reduction in soil pH may improve nutrient solubility in alkaline sandy soils. Available nitrogen, phosphorus, and potassium were also significantly higher under *S. italica*, indicating enhanced nutrient availability in the plant-associated rhizosphere. Arbuscular mycorrhizal fungal structures further suggest that plant–microbe interactions may contribute to nutrient cycling and soil functioning. However, the results should be interpreted cautiously because the study was based on a limited field comparison. Overall, *S. italica* may contribute to soil fertility improvement in nutrient-poor sandy soils and deserves further evaluation under controlled and replicated field conditions.

6. Limitations

This study compared two nearby field sites and used a relatively small sample size; therefore, the findings may not be broadly generalisable. Because the study was observational, pre-existing differences between vegetated and non-vegetated microsites could have influenced the results. Sampling depth, rainfall history, plant age, and duration of vegetation cover were not fully documented. Nitrogen fixation was inferred rather than measured directly, and arbuscular mycorrhizal fungal colonisation was observed but not quantified.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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