

MICROFLUIDIC APPROACHES IN SOIL SCIENCE, MICROBIAL PROCESSES AND ENVIRONMENTAL MONITORING: APPLICATION, CHALLENGES AND FUTURE PERSPECTIVES

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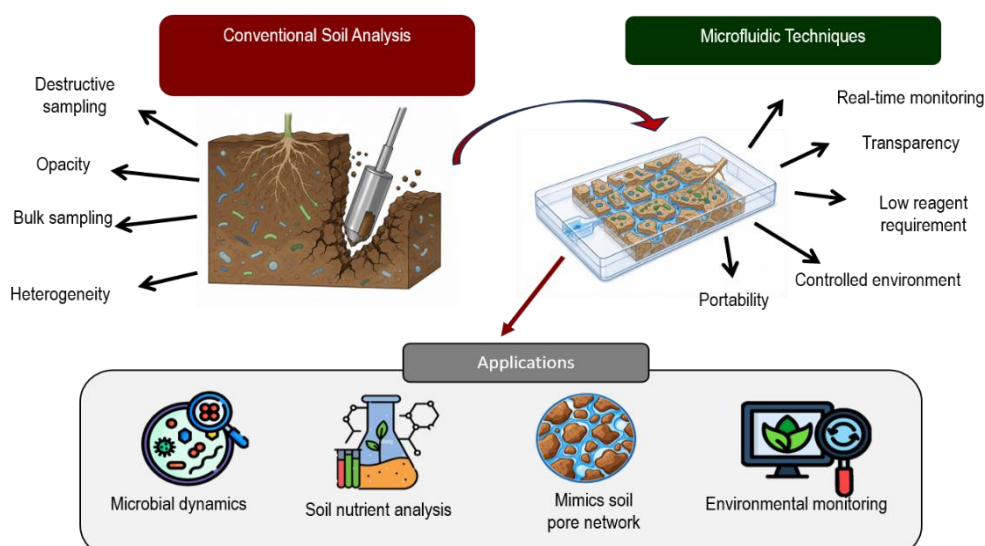
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ABSTRACT

Soil is a highly heterogeneous system where micro-scale interactions regulate key processes such as nutrient transport, microbial activity and plant growth. Conventional methods often rely on bulk measurements, destructive sampling and laboratory analysis, limiting the direct observation of pore-scale mechanisms. Microfluidics has emerged as a powerful tool to address these challenges by enabling precise manipulation of fluids within micro-scale channels that mimic natural soil pore structures. Entire analytic protocols including sample pretreatment, sample/reagent manipulation, separation, reaction and detection can be integrated into a single chip platform. This system enables controlled simulation of nutrient gradients, moisture dynamics and microbial habitats. This review summarizes the fundamentals of microfluidics, including device components, fabrication materials and techniques, along with its capability to mimic soil microenvironments. Further it also narrates the applications of microfluidics in soil science for nutrient analysis, studying microbial interactions and observing soil physical and geochemical processes. The transparency, less reagent requirement and efficiency of microfluidic system make it significant for future science. Despite challenges related to material limitations and system complexity, ongoing technological advancements are expected to enhance its applicability. Overall, microfluidics provides a promising platform for improving mechanistic understanding of soil processes and supporting sustainable agricultural and environmental management.

KEYWORDS: Microfluidics, Soil-on-a-chip, Soil microbial ecology, Nutrient sensing, Environmental monitoring, Precision agriculture

Graphical abstract



INTRODUCTION

Soil is a highly heterogeneous and dynamic multiphase system in which mineral constituents, organic matter, microorganisms, water, and gases interact across diverse spatial and temporal scales (Mansab et al. 2025; Tecon and Or 2017). As one of the most complex terrestrial ecosystems, soil plays a fundamental role in supporting plant growth, regulating biogeochemical cycles, and maintaining environmental sustainability (Bebber and Richards 2022; Zaman et al. 2025). However, its naturally opaque nature, irregular architecture, and pronounced spatial heterogeneity make direct investigation of microscale processes particularly challenging (Vogel et al. 2022). Conventional bulk-scale analytical approaches generally provide spatially averaged measurements, which can obscure the localized mechanisms occurring at the pore scale, including nutrient transport, microbial colonization, root–microbe interactions, mineral weathering, and water movement (Steefel et al. 2015). Consequently, many microscale soil processes are still understood primarily through indirect measurements and inference rather than through direct, real-time observation.

Microfluidics is an interdisciplinary field that involves the precise manipulation and control of fluids at micrometre to millimetre scales within microfabricated channels and chambers. This technology integrates principles from physics, chemistry, engineering, and biology to create miniaturised platforms capable of performing complex analytical and experimental tasks (Zhu et al. 2022). Microfluidic systems exploit unique physical phenomena that dominate at small scales, such as laminar flow, high surface-area-to-volume ratios, and rapid diffusion. These characteristics enable precise control over chemical gradients, temperature, and mechanical forces, making microfluidics particularly well-suited for studying biological and environmental processes that occur at the microscale (Stanley et al. 2016). These systems are commonly constructed from optically transparent materials like glass, silicon or PDMS, facilitating real-time visualization of physical, chemical, and biological interactions under well-defined environmental conditions (Massimiani et al. 2023). Microfluidic platforms provide a controlled experimental environment by precisely controlling channel dimensions, fluid flow rates, nutrient gradients, and microbial distributions for isolating individual variables and examining soil processes at the pore scale. Microfluidics has revolutionized biological and environmental research by providing unprecedented capabilities for observing and manipulating living systems at scales relevant to individual cells and microorganisms (Mafla-Endara et al. 2021).

Application of microfluidics to soil ecosystem research provides several key advantages. It enables direct observation of nutrient transport and diffusion under defined hydrodynamic conditions, examination of microbial behaviour at single-cell resolution, and investigation of root responses to chemical and mechanical gradients (Agarwal et al. 2024; Dai et al. 2025; Patko et al. 2024; Yang et al. 2021). Furthermore, microfluidic platforms facilitate quantitative analysis of biogeochemical reactions with high spatial and temporal precision, thereby linking microscale mechanisms to broader ecosystem functions (Böckmann et al. 2021; Zhang et al. 2018; Zhu et al. 2022).

Stemming from microelectronics and analytical chemistry, microfluidics was first applied to realise capillary electrophoresis in early 1990s showing its huge potential for miniaturised, sensitive, and high-throughput chemical analysis. Microfluidic platforms have the potential to address four major challenges in studying soil systems, namely (1) their enormous spatio-temporal heterogeneity, (2) lack of current methods to mimic soil realistically at the appropriate scale, (3) difficulties in studying interactions among soil microbes and (4) lack of optical access in real soil systems (Alekkett et al. 2018).

Microfluidic devices offer precise regulation of micro scale environmental parameters, including pore size, nutrient gradients, and fluid flow dynamics (Ugolini et al. 2024). Their small size and volume requirements reduce reagent consumption while maintaining high surface-to-volume ratios, which significantly enhanced the reaction efficiency and interaction sensitivity (Hajam and Khan 2024).

Thus, microfluidics serves as a critical bridge between simplified laboratory experiments and the inherent complexity of natural soils. By providing mechanistic insights into pore-scale interactions, this technology contributes significantly to advancing soil fertility management, sustainable agricultural practices, and predictive modelling of ecosystem responses to environmental change.

Advantages of Microfluidics in Soil Ecosystem Research

Compared to traditional equipment, microfluidic devices offer advantages such as low power and time consumption, lower costs of manufacturing and handling, greater flexibility, precise manipulation of liquids, reduced sample and reagent consumption, and the ability to maintain high throughput screening, rapid sample processing, accuracy, and resolution (Horowitz et al. 2020; Kulasinghe et al. 2018; Sinha et al. 2018). The advantages of microfluidic chips lie in their capacity to create controlled microenvironments; microfluidic chips have emerged as potent tools offering precise control over environmental parameters and real-time observations (Table 1). The high-throughput nature of these devices accelerates experimentation by facilitating simultaneous testing of various microbial strains and nutrient compositions. The inherent reduction in reagent consumption offered by microfluidics is both cost-effective and environmentally friendly. However, scaling up from micro scale findings to practical applications necessitates careful consideration (Wang et al. 2024).

Table 1. Advantages in microfluidics in soil ecosystem researches

Advantage	Importance in soil ecosystem research
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Visual access		Microfluidic soil chips are transparent, to observe microbial and mineral interactions at cell and pore scale.
In-situ soil ecology study		Chips can be incubated in soil or buried in field, making it possible to study soil ecology under near-natural conditions.
Understanding interactions	microbial	Soil chips help analyse inter-kingdom interactions, food-web dynamics, and feedbacks between microbes and pore structure.
Controlled microenvironment		Microfluidics provides precise control over moisture, nutrients, gradients, and physical structure, which is difficult in bulk soil.
Simulation of heterogeneity	soil	Soil-like pore networks, barriers, and gradients can be engineered to mimic the complexity of real soil habitats.
Single-cell level study		Gives unprecedented access to biological events at the level of individual cells or hyphal tips.
Real-time monitoring		Monitor microbial movement, colonization, and interaction dynamically rather than using endpoint sampling.
Link between lab and field		Connect controlled laboratory experiments with field microbial ecology.
Reduced sample requirement		Small quantity of sample and reagents are needed, making experiments economical and efficient.
Reproducibility		Chip geometry reproduce repeatedly, improving consistency across experiments.

Sources: Aleklett et al. (2018); Mafla-Endara et al. (2021); Stanley et al. (2016)

Limitations of Conventional Methods

Conventional approaches in soil analysis are generally based on bulk sampling, sample transfer, extraction, and laboratory-based measurements, which often involve destructive procedures (Lu et al. 2024). Although these methods are relatively simple, economical, and widely established, they provide limited insight into the fine-scale spatial organization of soil processes. The inherently opaque, heterogeneous, and mineral-rich nature of soil further complicates direct observation of microbial behaviour and interactions within individual microhabitats (Smercina et al. 2021). Consequently, use of large composite samples, for characterizing microbial communities at plot or field scales, can obscure microscale variations in soil structure and diminish the ability to resolve spatial patterns of microbial community assembly (Thakur et al. 2020).

A major limitation of bulk analysis is averaging of physical, chemical, and biological properties across relatively large spatial domains. Such averaging can mask microscale gradients in moisture, nutrients, oxygen, and other resources, as well as localized microbial hotspots and distinct microhabitats that regulate soil biochemical processes (Szoboszlay and Tebbe 2021). Furthermore, destructive extraction, preparation, and combustion procedures may disturb the original pore architecture and modify the biological and physicochemical conditions of the sample. This is particularly problematic when the objective is to investigate processes that are strongly dependent on the intact structure of soil microsites (Chen et al. 2024).

Traditional field and laboratory systems also offer relatively limited control over the individual microscale factors governing soil processes. Although field experiments and mesocosms provide valuable information under relatively realistic conditions, they are often unable to independently manipulate the physical and chemical gradients that control water movement, solute transport, nutrient availability and microbial interactions at the pore scale (Cao et al. 2024; Henri and Diamantopoulos 2023). Similarly, conventional methods for characterizing soil pore architecture may require complex sample preparation and highly controlled experimental conditions. Disturbance of the original soil structure during preparation can alter pore geometry and consequently introduce inaccuracies into the measurement of pore characteristics. Moreover, the inherent randomness, complexity, spatial variability, and autocorrelation of soil pore networks make their quantitative characterization using conventional techniques challenging (Wang and Zhang 2024).

Thus, conventional soil analytical methods remain valuable due to its relative simplicity, accessibility, and cost-effectiveness, they are inherently limited in resolving the dynamic and spatially heterogeneous nature of soil processes. The inability to simultaneously preserve microscale structure, visualize biological interactions and

precisely manipulate local environmental conditions creates a methodological gap in soil research. These limitations have stimulated the development of microscale and microfluidic approaches, which offer opportunities to investigate soil processes with greater spatial and temporal resolution while maintaining controlled experimental conditions.

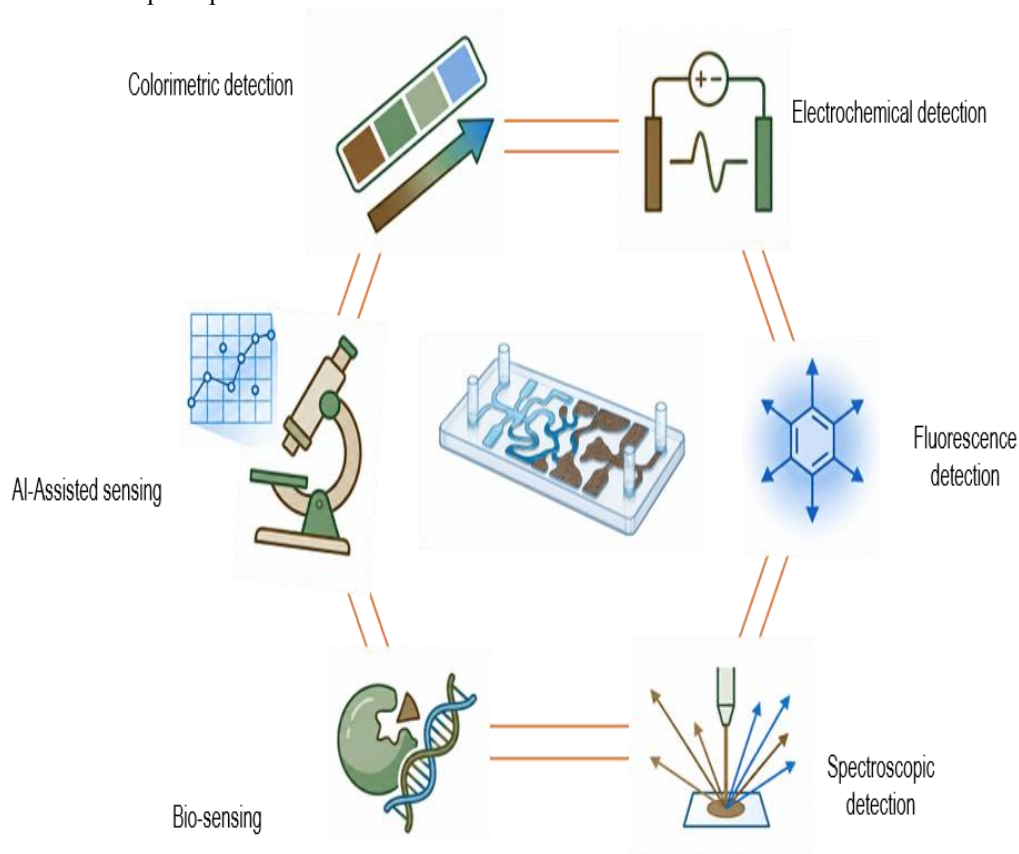
Detection Principle, Materials and Fabrication in Microfluidics

A microfluidic pore model (micro-model) which is applied in geo-system engineering should have the ability to tailor the topology and geometry of the model to suit the geo logical porous media. The micro-model should directly visualize the flow, transport, and reaction in porous media. Specific fabrication techniques and materials should be chosen for microfluidic devices to investigate different soil processes, considering the technical accessibilities, targeted functions of the microfluidic devices, as well as the compatibility with analytical and characterization techniques (Zhu et al. 2022).

Detection Principles in Microfluidic Platforms

The analytical capabilities of microfluidic systems are determined by the integration of sensitive and selective detection mechanisms capable of quantifying physical, chemical, and biological signals within microscale environments. Optical, electrochemical, spectroscopic, and biosensing approaches are among the most widely employed strategies for soil, environmental, and agricultural applications. Collectively, these analytical strategies have significantly expanded the applicability of microfluidic technologies across soil science, environmental monitoring, microbial ecology, and precision agriculture.

Figure 1. Detection principles in Microfluidic devices



Fabrication Materials

There are several types of micro-model fabrication materials (Table 2), including nonorganic materials (glass and silicon), polymeric materials like poly dimethyl siloxane (PDMS) and polymethyl methacrylate (PMMA), and common materials (soil, rock, cement, ceramics). Each material has different mechanical, thermal, and chemical properties, and is suited for a different fabrication method (Cao et al. 2019).

Fabrication Techniques

The fabrication technique plays a crucial role in determining the performance, reproducibility, and scalability of microfluidic devices. Over the years, a wide range of materials and fabrication approaches have been developed to meet diverse application requirements. Among these, photolithography, soft lithography, micro-injection moulding, hot embossing, laser ablation, and three-dimensional (3D) printing are the most widely employed techniques (Table 3). Each method offers distinct advantages and limitations in terms of resolution, material compatibility, fabrication cost, throughput, and ease of manufacturing, thereby influencing the selection of fabrication strategies for specific microfluidic applications.

Table 2. Materials for microfluidic device fabrication

Material	Advantages	Disadvantages	Citation
Silicon	Readily available, chemically compatible, thermostable, easily fabricated, and widely used in biological applications	Opaque to visible and UV light, fragile due to high elastic modulus, and challenging for valve and pump integration	Wang et al. (2024)
Glass	Chemically inert, thermostable, electrically insulating, rigid, biocompatible, optically transparent, easy to clean, and suitable for operation under extreme conditions	Expensive fabrication, cleanroom-dependent processing, and complex microfabrication requirements	Aralekallu et al. (2023)
PDMS	Low-cost, easy to mold, optically transparent, gas permeable, biocompatible, and ideal for rapid prototyping	Prone to small-molecule absorption, solvent incompatibility, swelling, and water evaporation	Raj M and Chakraborty (2020)
PMMA	Offers better solvent compatibility than PDMS, no small-molecule absorption, optical transparency, and amenability to surface modification	Limited chemical resistance compared to fluoropolymers	Kotz et al. (2020)
Paper-based Microfluidics	Extremely low-cost, accessible, porous, biocompatible, and suitable for capillary-driven flow and point-of-care diagnostics	Poor wet mechanical strength, limited transparency, and low flow-control precision	Panigrahy et al. (2025)

Table 3. Fabrication techniques to develop Microfluidics devices

Fabrication technique	Basic process	Typical materials
Photolithography	A microscale pattern is defined using light-based patterning on a substrate. The patterned regions are subsequently used to form the required microstructures/ channels.	Silicon, glass, polymers, paper
Soft lithography	A mould-based replication process is used to reproduce microscale channel patterns in a soft material such as PDMS.	PDMS and polymers
Etching	Selected portions of a substrate are removed using light and/or chemical etching to generate microscale channels and structures.	Silicon, glass
Micromachining micromilling	Material is mechanically removed to create microchannels. / In Lego microfluidics, micromilling is used to create channels before assembling the modified bricks into a device.	Lego/plastics

3D printing	The microfluidic device is additively fabricated to produce complex geometries and structures, enabling direct rapid prototyping and customization.	Polymers and biocompatible materials
Plasma treatment	The paper describes plasma treatment as an approach used in the fabrication of earlier paper-based microfluidic devices.	Paper
Wax printing	Wax is patterned onto the paper to create defined regions/barriers for fluid transport.	Paper
Inkjet printing/etching	Inkjet-based patterning or etching is used to generate microscale patterns on paper.	Paper
Laser treatment	Laser treatment is used to modify/pattern the substrate for producing microfluidic structures.	Paper/other substrates

Source: Boobphahom et al. (2020), Su et al. (2023)

Applications of Microfluidics

Microfluidics has been applied to a wide range of multidisciplinary areas, and many of these applications can be categorized under “lab-on-a-chip”. These themes encompass a diverse array of applications, including the manipulation of small fluid volumes, the creation of micro scale environments, and integration of biological components for various research purposes. Lab-on-a-chip (LoC) devices, also known as μ TASs, are miniaturized platforms that integrate multiple laboratory-based functions onto a single chip or substrate (Hajam and Khan 2024). The following areas of microfluidics application is commonly addressed in many literatures.

Soil properties and Processes

Soil nutrient dynamics and interfacial interactions sit at the heart of what makes soil a living, functioning ecosystem rather than an inert growth medium. Yet these processes—nutrient release, uptake, transport, and the chemical exchanges occurring at mineral, water, and organism boundaries which unfold at scales and speeds that conventional bulk analysis struggles to capture. Traditional soil testing methods, dependent on extraction and laboratory processing, offer only a retrospective, averaged snapshot of conditions that are in reality highly dynamic and spatially variable at the pore scale.

Microfluidic technologies offer a way to close this gap. By miniaturizing analytical workflows directly onto a chip, researchers can extract, filter, and detect soil nutrients with far greater speed and precision than conventional approaches allow, while simultaneously recreating the physical architecture of soil pores to observe interfacial processes as they actually occur. Table 4 examine how these platforms have been applied to two closely related fronts: first, the rapid, on-chip detection and quantification of key plant-available nutrients such as nitrate, nitrite, potassium, and phosphate; and second, the investigation of the complex physical and chemical interactions occurring at soil interfaces, including mineral weathering, carbon–clay sorption, colloid transport, and fluid–mineral reactions. Together, these applications illustrate how microfluidics is enabling researchers to move from indirect, bulk-scale inference toward direct, real-time observation of the mechanisms that ultimately govern soil fertility and nutrient cycling.

Table 4. Application in Soil processes

Microfluidic approach / platform	Soil process / target	Significance	Major findings	Study
PDMS microchannel with K-feldspar-bearing syenite	K ⁺ release and mineral weathering	Highlighted the role of rhizosphere-scale flow in nutrient release. Supported silicate minerals as alternative K fertilizers.	Enabled measurement of K ⁺ release at 10–100 µm spatial and 10–100 min temporal scales. Revealing faster K ⁺ availability at root-relevant scales than conventional methods.	Ciceri and Allanore (2015)
Mobile lab-on-a-chip using capillary electrophoresis and conductivity detection	NO ₃ ⁻ , NH ₄ ⁺ , K ⁺ and PO ₄ ³⁻ detection	Early demonstration of portable microfluidic soil nutrient analysis for rapid field assessment.	Portable sensor enabled on-site analysis of four major nutrient ions in soil extracts	Smolka et al. (2016)
Real Rock-Microfluidic Flow Cell (RR-MFC)	Pore-scale flow, transport and multiphase behaviour	Advanced realistic porous-media model preserving natural mineralogy and pore architecture	Enabled real-time visualization of flow and transport through natural rock pore networks	Singh et al. (2015)
2D soil-on-a-chip with controlled upward fluid flow	Granular rearrangement, fluidization and channelization	Demonstrated dynamic soil structure and pore-scale mechanical responses using microfluidics	Particle rearrangement and compaction occurred below the instability threshold, while higher flow induced vertical channels, compaction, and dilation.	Houssais et al. (2019)
Smectite-clay microfluidic system with confocal imaging	Clay–carbon interactions and C protection	Links clay mineralogy, microbial activity and soil carbon stabilization.	Bacteria were excluded from clay aggregates, while enzymes penetrated and released carbon	Yang et al. (2021)
Microfluidic chip with porous ceramic filter for soil-solution extraction	Soil-water extraction and nutrient sampling	Provides the sampling interface needed for integrating microfluidics with continuous soil nutrient analysis.	Soil-solution extraction varied with soil moisture and texture	Böckmann et al. (2021)
Transparent soil microchips with field-buried devices	Microbial dispersal, pore connectivity and soil ecology	Visualized soil microbial interactions within realistic pore structures	Fungal hyphae enhanced bacterial and protist dispersal by up to 32% and 16%, respectively	Mafla-Endara et al. (2021)
Autonomous droplet microfluidic analyzer coupled with microdialysis/ultrafiltration	In situ nitrate monitoring	Enabled continuous, autonomous soil nutrient monitoring and precision fertilizer management	Used 96 µL reagent per measurement, with <10% error (microdialysis) and 2–3% (ultrafiltration), enabling field monitoring of nitrate changes	Lu et al. (2024)
Microfluidic impedimetric e-tongue with CrN, BN and TiN sensing films	K, Mg and other macronutrient detection	Enabled rapid, multiplexed, field-deployable nutrient sensing	Differentiated nutrient-rich soils without pretreatment, with strong K and Mg resolution	Boeira et al. (2025)

Computationally optimized microfluidic channel using CFD, RSM and statistical optimization	Soil nitrite detection	Demonstrates integration of microfluidics, computational fluid dynamics and statistical/optimization approaches for soil nutrient sensing.	Optimized channel geometry for nitrite detection in soil samples (2.81–4.18 ppm)	Khomane and Jadhav (2025)
Particle-filled, droplet and long-distance microfluidic chips	Microbially induced CaCO_3 precipitation	Relevant to soil stabilization, biocementation and biogeochemical engineering	Enabled real-time visualization of bacterial growth, detachment, bacteria-crystal interactions and CaCO_3 crystal growth	Wang et al. (2024)

Soil Microbial Processes

Microbial processes in soil is complicated physically and chemically structured environment, which is characterized by porous soil architecture, diverse components and interfacial properties, coupled with heterogeneous distribution of water, solutes, gases, and microbes (Harvey et al. 2020; Stanley et al. 2016). Multiple features make microfluidics a promising technology for exploring soil microbial processes (Wu and Dekker 2016; Zhang et al. 2022). Nanofabrication technologies allow cultivating and observing microbes from single-cell to population level, as well as co-cultivation of multispecies, in artificial soil habitats (Burmeister and Grünberger 2020; Leygeber et al. 2019).

The microenvironments, such as temperature oxygen, flows, and chemical gradients, precisely manipulated as being constant or oscillating, homogeneous or heterogeneous (Somaweera et al. 2016). Such systems enable the study of microbial interactions, spatial organization, and responses to heterogeneous nutrient patches (Table 5). Additionally, microfluidic devices have facilitated the cultivation of previously un-culturable soil microorganisms by providing microhabitats that closely resemble natural soil conditions (Alekkett et al. 2018).

Together, these studies demonstrated that microfluidic technologies provide unique opportunities to investigate soil microbial processes at pore scale, improving our understanding of microbial interactions, movement, and ecological dynamics within soil ecosystems.

Table 5. Application in understanding microbial processes

Microfluidic device	Key findings	References
Nanofabricated artificial soil habitat	Allowed cultivation and observation of microbes from single-cell to population level and multispecies co-culture.	Burmeister and Grünberger (2020), Leygeber et al. (2019)
Droplet microfluidics	Improved recovery of diverse and rare microbial taxa compared with conventional culture methods.	Dai et al. (2025)
Pore-scale confinement chip	Revealed species-specific fungal hyphal responses to nutrient limitation.	Baranger et al. (2020)
Narrow-channel microfluidic system	Showed that bacterial motility is strongly influenced by spatial confinement and cell trapping.	Tokárová et al. (2021)
Chemotaxis microfluidic chip	Demonstrated bacterial transverse migration from high- to low-permeability regions.	Wang et al. (2016)
Microfluidic soil chip with deep learning-assisted image analysis (Mask-RCNN)	Enabled automated quantification of bacterial abundance, morphology, aggregation, and community dynamics in transparent soil habitats, reducing the limitations of manual microbial analysis.	Zou et al. (2024)
Microbial signaling chip	Chemical cues from <i>Listeria monocytogenes</i> influenced the chemotactic movement of <i>Euglena</i> .	Gaines et al. (2019)
Microfluidic plates with OPTIR spectro microscopy	Enabled mapping of microbial growth, turnover, and necromass formation across soil microhabitats with varying pore connectivity, oxygen, and nutrient gradients.	Bentvelsen et al. (2025)
Droplet-based micro-segmented flow microfluidic system	Enabled high-resolution assessment of soil microbial community responses to copper stress, identification of microbial tolerance thresholds (EC50: 0.24-1.00 mM Cu),	Kürsten et al. (2015)

and isolation of highly copper-tolerant microorganisms up to 9 mM Cu.

Root-on-a-chip device	Directly observed chemotactic migration of <i>Bacillus subtilis</i> to roots and exclusion of <i>E. coli</i> from the root surface.	Aufrecht et al. (2018), Massalha et al. (2017)
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Environmental monitoring

Microfluidic devices are characterized by their compact and portable nature, facilitating their deployment in remote locations with ease. These devices lend themselves well to automation, resulting in cost savings for analysis and enhanced consistency in the obtained results. These demonstrate versatility in analysing a wide array of pollutants (Tudi et al. 2022), encompassing organic chemicals, inorganic chemicals, and biological agents (Hajam and Khan 2024). Microfluidic platforms offer promising tools for environmental monitoring by enabling sensitive detection of pollutants such as gases, pesticides, and heavy metals. Their portability, low reagent consumption, and rapid response make them particularly suitable for real-time environmental assessment.

Pesticide detection

Pesticides play a vital role in modern agriculture by effectively managing pests to meet global food production demands. However, with over three billion kilograms of pesticides consumed worldwide annually, their extensive usage has raised concerns regarding the presence of pesticides and pesticide residues in environment (Tudi et al. 2022). There are many studies focusing on pesticide detection using microfluidic techniques in recent years (Table 6). Researchers have explored various innovative methods for detection and commonly employed rapid pesticide detection techniques utilizing microfluidics include enzyme inhibition, immunoassays, molecular imprinting, etc. Microfluidics platforms provide rapid, low-cost, and portable alternatives for pesticide monitoring. Their ability to integrate electrochemical and colorimetric sensing with digital image analysis makes them promising tools for environmental monitoring and precision agriculture.

Table 6. Microfluidic devices in Environmental monitoring and Pesticide detection

Study	Target analyte	Microfluidic platform / material	Detection principle	Key analytical performance	Critical interpretation
Wang et al. (2022)	Cu ²⁺ , Pb ²⁺ and Ag ⁺	Integrated microfluidic chip with capillary valves, DNAzyme-functionalized microparticles, and trapping zones	DNAzyme-mediated cleavage followed by gravitational–magnetic separation and distance-based visual readout	LOD: 103.1 nM Cu ²⁺ , 69.5 nM Pb ²⁺ and 793.6 nM Ag ⁺	Integrated point-of-use monitoring with sample metering, reaction, separation, and readout in one platform
Catalan-Carrio et al. (2022)	NO ₂ [−] and NO ₃ [−]	PMMA handheld platform with paper nitrate-reduction unit and Griess-reagent ionogel	Colorimetric Griess assay with nitrate-to-nitrite reduction and smartphone-based imaging	LOD/LOQ: 0.47/0.68 mg L ^{−1} for nitrite and 2.3/3.4 mg L ^{−1} for nitrate	Enabled portable nitrate monitoring in environmental waters Sensitivity was limited by ~20% nitrate-to-nitrite conversion and slow colour stabilization.
Lafuente et al. (2020)	Paraoxon-methyl	PDMS lab-on-chip with Au@POM SERS nanostructures fabricated using 3D-printed molds	Surface-enhanced Raman spectroscopy (SERS)	LOD: 1.67 × 10 ^{−7} M (41.4 µg L ^{−1}) for Au@PW and 2.11 × 10 ^{−7} M (52.1 µg L ^{−1}) for Au@PMo	Enabled real-time pollutant sensing with reusable surfaces,
Wu et al. (2022)	Profenofos and methomyl	Three-layer wax-printed paper microfluidic chip with smartphone integration	Acetylcholinesterase inhibition + chromogenic reaction + smartphone RGB/gray-value analysis	LOD: 55 nM profenofos and 34 nM methomyl; linear ranges 0.27–2.1 and 0.14–1.85 µM, respectively	Low-cost smartphone-integrated pesticide monitoring with improved reagent retention, but camera variability and limited

								pesticide selectivity remain challenges
Moulahoum (2023)	Atrazine	Laser-printed μ PAD containing AgNPs and AuNPs, smartphone-assisted image analysis	Nanoparticle-based dual colorimetric sensing	LOD: 3.52 μ M (AgNPs) and 10.97 μ M (AuNPs);				Simple fabrication with smartphone detection, but limited by simulated samples and a higher detection limit
Ozhikandathil et al. (2018)	NH ₃ (ammonia)	Optical microfluidic device incorporating a PDMS–ninhydrin composite	Optical/colorimetric detection based on ammonia-induced change in the ninhydrin–PDMS composite	Detection down to 2 ppm NH ₃ ;				Demonstrated miniaturized gas sensing for environmental monitoring, but with limited trace-level detection capability

Challenges

Despite the significant advantages of microfluidic technologies in studying soil ecosystem dynamics, several technical and methodological challenges limit their broader application. The major limitation is the reliability and sensitivity of detection techniques integrated within microfluidic platforms. Microfluidics engineering faces several interconnected challenges. Fabrication and integration are difficult: techniques like soft lithography are powerful but complex and costly, raising concerns about reproducibility and scalability, and integrating multiple components (pumps, sensors, valves) into one device adds further complexity and points of failure.

Precise fluidic control is hard to maintain, especially at low flow rates, since microscale effects can easily disrupt the stable fluid behaviour that accurate measurements depend on. Device surfaces must also be engineered to resist biofouling over long-term use while staying biocompatible with biological samples—a challenge requiring combined expertise in materials science, surface engineering, and biocompatibility testing.

These devices generate large volumes of data, and turning that into meaningful insight which requires robust analytical pipelines, without this much of their potential value goes unrealized. Performance is also constrained by its small size and high surface-to-volume ratio that make microfluidics useful in the first place—causing flow instability, mixing difficulties, and accuracy limits—and precision achieved at small scale often becomes harder to preserve when scaling up for clinical manufacturing.

Commercialization is hindered by bulky auxiliary equipment and a lack of interchangeable components across vendors, keeping many systems stuck in the "Death Valley" between academic research and industry-ready products. This is compounded by a broader lack of standardization— incompatible platforms and the absence of standardized interfaces make it hard to compare results or collaborate though standardization efforts could ultimately streamline production and accelerate adoption. Finally, materials and manufacturing methods that work for small-scale academic prototypes often aren't suited to mass production, and moving from concept to market requires navigating additional feasibility and commercial considerations.

Overall, microfluidic technologies offer powerful tools for investigating soil processes at microscale, addressing these challenges will be essential to improve the reliability, realism and broader applicability of microfluidic platforms in soil ecosystem research.

Future perspectives

Microfluidic technologies are likely to be instrumental in providing more details on how soils function as ecosystems by allowing the measurements of physical, chemical, and biological processes at higher resolution. As device fabrication, sensing integration, and data analysis continue to advance, microfluidic technologies become more widely adopted in the fields of environmental monitoring and soil science.

Commercialization of microfluidics has lagged behind its academic progress, largely due to the difficulty of mass-producing precise systems, high setup costs, and industry reluctance to adopt new technology given steep initial investment. Most research still appears in specialized technical journals, and there's no guaranteed path to wider adoption—but researchers now have decades of experience to build on.

A key future direction is stronger collaboration between engineers and end-users like clinicians and biologists, moving away from the early assumption that non-engineers would simply adapt to complex tools. Simplifying adoption through user-friendly designs (like automated μ PADs) and better packaging/distribution can also lower barriers to entry.

Open-access repositories for designs, protocols, and data could accelerate progress by helping researchers build on each other's work, while highlighting successful case studies—improved efficiency, reduced reagent use, better data quality—can help drive broader interest.

Growing dataset complexity will require closer collaboration with data scientists and bioinformaticians to develop better analysis tools. The field should also address its environmental footprint through sustainable materials and

greener fabrication methods. Ultimately, advancing microfluidics into mainstream biomedical use will depend on global collaboration and sustained funding to support knowledge exchange and technology transfer.

CONCLUSION

Soil remains one of the most complex and heterogeneous systems in terrestrial ecology, and its opacity has long limited direct, real-time observation of the microscale processes that govern nutrient cycling, microbial interactions, and biogeochemical transformations. Conventional bulk-sampling approaches, though accessible and well-established, but inherently destructive and provide spatially averaged measurements that mask the pore-scale dynamics driving soil function. Microfluidic, or "soil-on-a-chip," platforms address this methodological gap by recreating soil pore architecture in transparent, precisely controllable microenvironments, enabling direct visualization of nutrient transport, microbial behaviour, root interactions, and mineral–water reactions at spatial and temporal resolutions unattainable through traditional methods.

This review has outlined the key advantages of microfluidics which brings to soil ecosystem research such as reduced reagent consumption, real-time monitoring, single-cell resolution, and the ability to simulate soil heterogeneity under controlled conditions alongside the diverse materials and fabrication techniques available to tailor devices for specific applications, from mineral weathering studies to pesticide and nutrient sensing. The breadth of documented applications, spanning soil interfacial processes, microbial ecology, and environmental monitoring, demonstrates that microfluidics has already begun bridging the gap between simplified laboratory experiments and the complexity of natural soils.

At the same time, significant challenges remain unsolved. Precise fabrication and integration, reliable fluidic control, biocompatibility, and the management of large, complex datasets all constrain current device performance. Scaling these systems from proof-of-concept prototypes to field-deployable, commercially viable tools is further complicated by bulky auxiliary equipment, a lack of standardization across platforms, and variability in materials suited to mass production. These limitations mean that, despite strong academic interest, microfluidic soil technologies have yet to achieve widespread adoption outside specialized research settings.

Looking forward, overcoming these barriers will require closer collaboration between engineers, soil scientists, and data specialists; simplified, user-friendly device designs; open-access sharing of protocols and data; and sustained investment in, scalable fabrication methods. As these efforts mature, microfluidics is well positioned to become an indispensable tool for mechanistic soil research deepening our understanding of pore-scale processes while supporting more sustainable, precision-based approaches to agricultural and environmental management.

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Authors contributions

Krishna Priya Matheth prepared the original draft of the manuscript. Chitdeshwari Thiagarajan provided overall supervision and contributed to critical review and editing of the manuscript. Backiyavathy M.R., Marimuthu S. and Boominathan P. edited the manuscript and all authors have read and approved the final version of the manuscript.

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