Rev Environ Sci Biotechnol
https://doi.org/10.1007/s11157-025-09730-w

REVIEW

A comprehensive review of impacts of soil management practices and climate adaptation strategies on soil thermal conductivity in agricultural soils

Ahmed Abed Gatea Al-Shammary · Layth Saleem Salman Al-Shihmani · Jesús Fernández-Gálvez · Andrés Caballero-Calvo

Received: 26 March 2025 / Revised: 14 May 2025 / Accepted: 21 May 2025

Abstract Soil thermal conductivity (λ) is a critical property influencing heat transfer in agro-environmental systems (A-ES), affecting soil temperature, water dynamics, and nutrient availability. Understanding the impact of soil management practices (SMP) and climate adaptation strategies (CAS) on λ is essential for optimizing agricultural productivity and ensuring soil sustainability. This review examines the influence of conventional and conservation tillage, crop rotation, mulching, and organic matter incorporation on soil λ. Conventional tillage practices often disrupt soil structure, reducing water retention and altering soil thermal characteristics (TCs), while conservation tillage enhances soil aggregation and moisture conservation, leading to improved λ. Crop rotation and mulching regulate soil microclimates, minimizing temperature fluctuations and contributing to thermal stability. Additionally, the review highlights the significance of soil texture, moisture content, and organic matter in determining λ. With increasing climate variability, integrating SMP and CAS can mitigate adverse effects on TCs, promoting resilience in agricultural systems. However, knowledge gaps remain regarding the long-term impacts of these strategies on λ across diverse soil types and climatic conditions. Future research should focus on developing integrated approaches that optimize SMP and CAS for improved λ, ensuring sustainable agricultural practices. Expanding studies on soil thermal dynamics will improve our ability to develop adaptive management strategies that support long-term soil health and productivity. This review underscores the necessity of sustainable soil management in the face of climate change, providing insights for future research and practical applications in agricultural systems.

Keywords Soil heat transfer · Soil management practices · Climate adaptation · Tillage systems · Mulching · Soil health

A. A. G. Al-Shammary (✉) · L. S. S. Al-Shihmani
Department of Soil and Water Science, College of Agriculture, University of Wasit, Kut, Iraq
e-mail: agatea@uowasit.edu.iq

L. S. S. Al-Shihmani
e-mail: lsalman@uowasit.edu.iq

J. Fernández-Gálvez · A. Caballero-Calvo (✉)
Department of Regional Geographical Analysis and Physical Geography, University of Granada, 18071 Granada, Spain
e-mail: andrescaballero@ugr.es

J. Fernández-Gálvez
e-mail: jesusfg@ugr.es

1 Introduction

Soil thermal conductivity (λ) is a fundamental property influencing heat transfer within soil structures, significantly impacting agricultural productivity and ecosystem health (Xia, 2025; Chen, 2024a; Wu,

Published online: 09 June 2025

2025a). It plays a crucial role in root development (Malek et al. 2021), microbial activity (Shah et al. 2024b), nutrient cycling (Lunt et al. 2023), and water dynamics (Fu et al. 2024a, 2024b), making it a key factor in agro-environmental systems (A-ES) (Muhudin et al. 2024; Pan et al. 2024). As global climate conditions continue to change, understanding the influence of soil management practices (SMP) and climate adaptation strategies (CAS) on λ is essential for optimizing A-ES, as illustrated in Fig. 1, showed the SMP—including tillage systems (TS), soil organic matter (SOM) management, irrigation practices (IP), crop rotation (CR), nutrient availability, soil texture, soil mineral content, soil temperature regimes, water dynamics, and overall soil structure—directly alter soil moisture content, organic matter levels, and soil thermal characteristics (TCs) (Al-Shammary et al. 2020b; Doneva et al. 2022; Fu et al. 2024b; Haque et al. 2024; He et al. 2024; Kolawole et al. 2024; Mirghafari et al. 2024; Song et al. 2024b; Wessolek et al. 2023; Wu et al. 2025b).

For instance, conventional tillage disrupts soil aggregates, increasing air-filled pores and reducing heat transfer efficiency (Abed Gatea Al-Shammary et al. 2022; Haque et al. 2024). In contrast, incorporating SOM enhances water retention (Esmaeilian et al. 2023; Fu et al. 2023b), thereby increasing λ due to water's superior thermal capacity (Usowicz and Lipiec 2020). Conservation tillage practices, such as no-till farming, help preserve soil integrity and maintain higher moisture levels, thereby moderating temperature fluctuations and improving thermal stability (Cárceles Rodríguez et al. 2022; Haque et al. 2024; Srivastava et al. 2024).

Understanding these factors is crucial for optimizing SMP to enhance TCs and agricultural productivity. This review aims to analyze the relationship between SMP, CAS, and λ to provide insights into sustainable soil management strategies that improve long-term soil health and resilience in agricultural systems.

1.1 Significance of the review

This review highlights the critical role of soil λ in agro-environmental systems (A-ES). Understanding how SMP and CAS influence λ is essential for optimizing agricultural productivity and ensuring

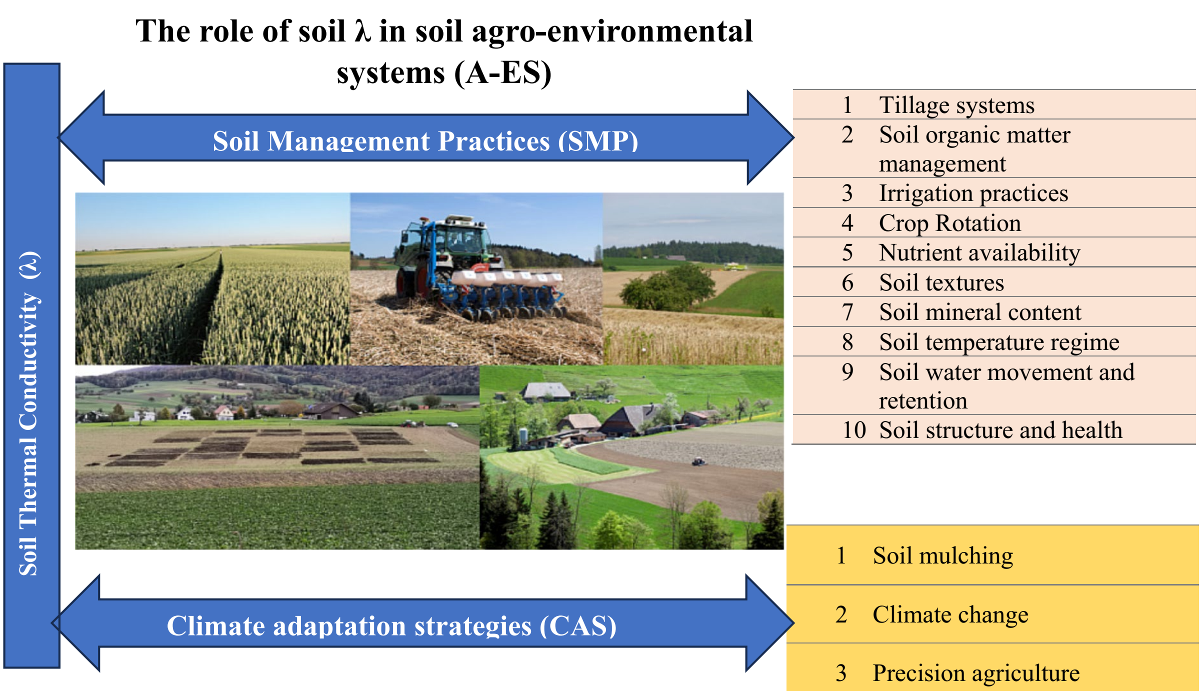

Fig. 1 Role of soil λ in soil agro-environmental systems

long-term soil health. This study explores the complex interactions between soil characteristics, water dynamics, nutrient availability, and microbial activity—all of which are directly affected by soil λ.

Additionally, the review provides valuable insights into the relationship between tillage methods, soil temperature regulation, and moisture retention within A-ES. Beyond its scientific significance, this work offers practical guidance for farmers and agronomists seeking to implement sustainable soil management strategies that improve TCs and improve overall soil performance.

By applying the findings from this study, agricultural practitioners can further improve soil health, increase crop productivity, and improve resilience to climate-related challenges. Furthermore, this review contributes to global efforts aimed at achieving food security and promoting environmental sustainability for future generations.

1.2 Objectives

This review aims to examine the key factors influencing soil λ in agricultural systems. The specific objectives are as follows:

1. Analyze the impact of SMP on soil λ. This includes a detailed evaluation of practices such as tillage systems, organic matter management, and soil mulching. By understanding these relationships, the review seeks to identify effective SMP that improve soil λ, ultimately enhancing crop productivity and soil health.
2. Explore the integration of CAS with soil λ. This involves assessing approaches such as mulching, cover cropping, and irrigation management that mitigate the effects of climate variability while optimizing soil λ. Understanding these strategies is crucial for building resilient agricultural systems capable of sustaining productivity under changing climatic conditions.
3. Identify knowledge gaps and propose future research directions. The review highlights key areas requiring further investigation, including studies on different soil types, the role of soil organic matter in thermal regulation, and the potential of precision agriculture technologies for better soil λ. These insights aim to support researchers and practitioners in implementing effective SMP that improve agricultural productivity and promote sustainable agro-environmental systems.

2 Materials and methods of review

This review paper used a method for examining recent studies on soil management practices (SMP), climate adaptation CAS, and their effects on soil λ. The present investigation mainly used Scopus and Web of Science because of their thorough coverage of academic journals in agriculture and environmental science To find relevant research, particular keywords were used, which includes but not limited to: "Soil Management Practices," "Soil Thermal Conductivity," "Conventional and Conservation Tillage," "Crop Rotation," "Mulching," "Organic Matter," "Soil Structure," "Reducing Water Retention," "Soil Microclimates," "Soil Temperature Fluctuations," "Soil Health," "Soil Organic Matter (SOM) Management," "Irrigation Practices," "Nutrient Availability," "Soil Mineral Content," "Climate Change," and "Precision Agriculture."

The review focused on papers released mostly from 2020 to 2025 to include the latest improvements and findings in the field. We found and evaluated 142 studies based on specific search requirements and acceptance or exclusion criteria. These studies provided a thorough examination of current understanding concerning soil management strategies and their impact on soil λ and overall soil health. The 142 studies were divided by paper types: original research (122), review articles (8), case studies (3), meta-analyses or modelling studies (6), and policy-oriented papers (3). This classification was established based on titles, journal emphasis, and conventional academic categories.

3 Principles, mechanisms, and agro-environmental significance of soil λ

Soil λ is a fundamental property that governs heat transfer within the soil matrix, significantly influencing agro-environmental systems (A-ES). It is defined as the rate of heat flow per unit area under a unit temperature gradient, typically expressed in watts per meter per degree Celsius (W/(m °C)) (Wu et al.

2025b). Heat transfer in soil occurs through three primary mechanisms: conduction, convection, and radiation (Fig. 2) (Najafian Jazi et al. 2024; Romio et al. 2022; Zimmer et al. 2023). Among these, conduction is the dominant process, strongly affected by soil composition, moisture content, structure, and organic matter levels.

Soil λ is a critical factor in A-ES, influencing various physical, chemical, and biological processes essential for agricultural productivity and soil health (Ding et al. 2021; Hu et al. 2022; Wang et al. 2023b). It affects root development, microbial activity, nutrient cycling, and water dynamics, all of which play vital roles in crop growth and soil sustainability. Effective soil management practices (SMP) such as tillage systems, organic matter incorporation, mulching, and irrigation strategies directly modify soil λ, thereby regulating soil temperature, moisture retention, and overall thermal stability.

Accurate assessment of soil λ is crucial for optimizing agricultural systems. Measurement techniques include steady-state and transient methods, along with advanced sensor-based approaches (Al-Shammary et al. 2022; Fu et al. 2024a; Kashyap & Kumar 2021). Additionally, empirical, numerical, and mixing models are used to simulate and predict soil heat transfer under varying environmental conditions (Sepaskhah & Mazaheri-Tehrani 2024; Song et al. 2024b; Xia et al. 2025). Understanding soil λ dynamics and its interaction with SMP is essential for enhancing agricultural resilience, improving productivity, and promoting sustainable land management in the face of climate change.

3.1 Influence of soil management practices (SMP) on soil thermal conductivity (λ)

Soil management practices significantly influence soil λ by altering key soil properties such as structure, μ, OMC, and ρb. These factors collectively determine the soil's ability to transfer heat efficiently.

3.1.1 Tillage Systems (T_s)

Tillage systems are crucial in determining soil TCs by altering soil physical characteristics that govern heat transfer. The effect of tillage on soil λ is complex, as it depends on the type of tillage system used and the depth at which tillage is applied (Al-Shammary et al. 2022; Liebhard et al. 2022; Thotakuri et al.

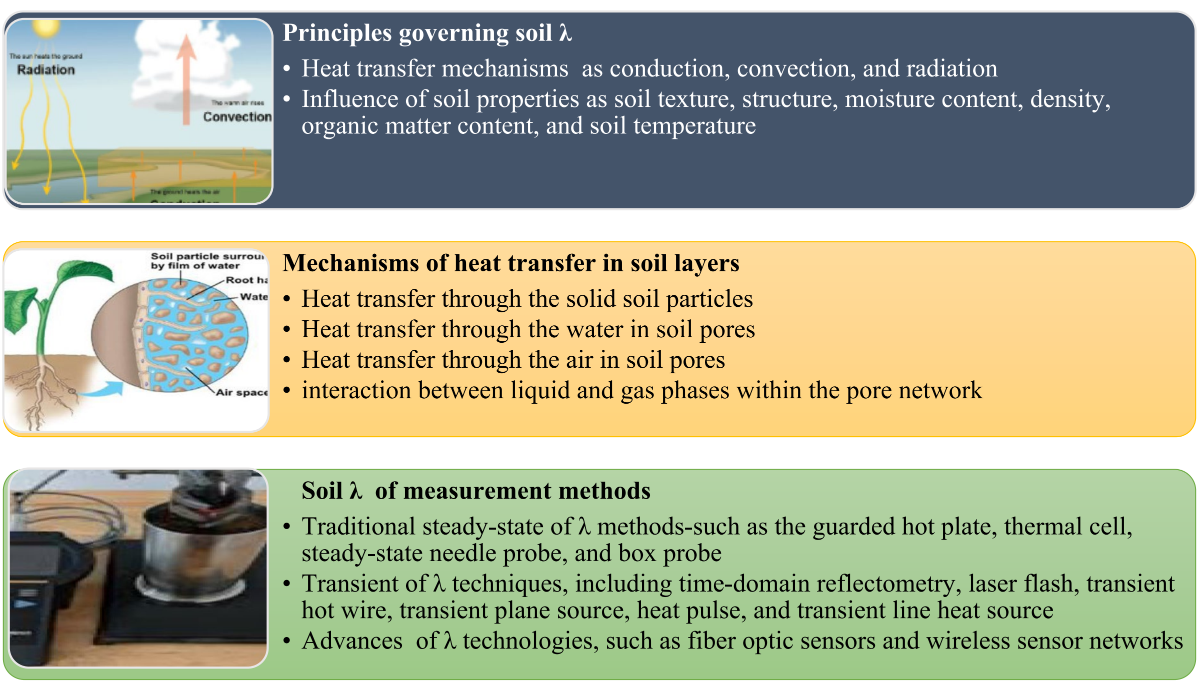

Fig. 2 Principles, mechanisms, and measurements of soil λ

2024). Figure 3 illustrates how different tillage methods affect soil λ by influencing soil structure, moisture retention, and temperature regulation (Al-Shammary et al. 2024; Song et al. 2024a; Yin et al. 2023; Tschanz et al. 2024).

Conventional tillage ($Tillage_{trad}$) and conservation tillage ($Tillage_{cons}$) have distinct impacts on soil λ. Conventional tillage typically results in reduced ρb and increased porosity (Φ), enhancing the soil's ability to transfer heat (Gatea Al-Shammary et al. 2023; Wang et al. 2023c). This increase in porosity allows for more efficient heat conduction, improving λ. However, this also leads to greater temperature fluctuations because the soil is more exposed to air, which has a lower thermal capacity than water. Therefore, while conventional tillage increases heat transfer, it also makes the soil more susceptible to rapid temperature changes, which may adversely affect plant growth and microbial activity (Song et al. 2024a).

In contrast, conservation tillage preserves soil structure by minimizing soil disruption. This results in better moisture retention and higher organic matter content, which increases the soil's heat storage capacity (Cárceles Rodríguez et al. 2022; Haque et al. 2024). Because water has a higher thermal capacity than air, maintaining moisture in the soil increases λ. At the same time, conservation tillage reduces the rate of temperature fluctuations in the soil. This enhanced thermal stability is beneficial for maintaining optimal growing conditions for plants and supporting consistent microbial activity.

The depth of tillage also affects λ. Deeper soil layers generally have lower λ due to increased compaction and reduced porosity (Al-Shammary et al. 2020a; Liu et al. 2024a). Shallow tillage primarily influences the upper soil layers, where temperature fluctuations are more pronounced. As a result, shallow tillage practices often alter λ at the soil surface, affecting the heat dynamics and influencing soil temperature regulation.

In addition to tillage systems, the composition of the soil itself plays a significant role in determining λ. For example, soils rich in quartz tend to have higher λ, while higher clay content and increased porosity generally reduce λ (Xiuling et al. 2024). Extrinsic factors such as seepage velocity and salinity also influence λ. Increased seepage velocity tends to increase heat transfer, while lower salinity levels generally reduce λ (Cheng et al. 2024; Malek et al. 2021). Soil moisture content, in particular, is a major determinant of λ; saturated soils, for instance, exhibit higher λ because water conducts heat more effectively than air (Wu et al. 2025b).

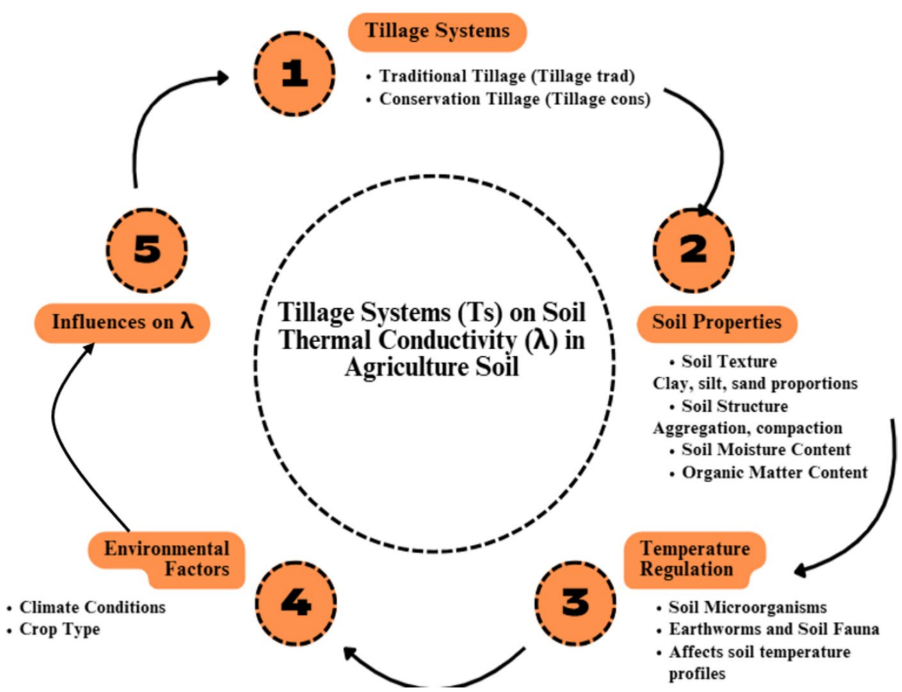

Fig. 3 Soil λ effect by tillage practices

Understanding the relationship between soil λ and tillage systems is crucial for optimizing agricultural practices. By selecting appropriate tillage methods, farmers can improve soil structure, moisture retention, and thermal stability, leading to more efficient soil heat transfer. Advanced soil monitoring techniques allow for precise measurements of λ, helping farmers to manage soil properties better and adapt to changing climatic conditions. Ultimately, incorporating effective SMP can enhance crop yields, improve soil health, and contribute to sustainable agricultural practices.

3.1.2 Soil organic matter (SOM) management

Soil organic matter (SOM) plays a crucial role in regulating soil λ, as it directly affects soil structure, Φ, water retention, and nutrient availability (Nutri $_{av}$), all of which influence agricultural productivity. As shown in Fig. 4, the relationship between SOM and λ is complex, with SOM influencing several physical properties of the soil that ultimately affect heat transfer (Allende-Montalbán et al. 2024; Chen et al. 2024c; Fu et al. 2024b; Tian et al. 2025). While SOM can improve soil structure by improving water retention and nutrient cycling, it also tends to decrease the soil's ability to transfer heat due to its inherently lower λ compared to mineral soil components (Xiuling et al. 2024).

Studies have shown that soil λ typically decreases as the conditional nature of SOM's concentration increases (He et al. 2021; Pan et al. 2024; Usowicz and Lipiec 2020; Wessolek et al. 2023; Zhu et al. 2019). This is primarily because organic matter, being less thermally conductive than mineral particles, reduces the overall λ of the soil (He et al. 2021). As SOM concentration rises, particularly in saturated soils, the reduction in λ becomes more pronounced. While SOM provides numerous benefits for soil health, such as enhancing microbial activity and supporting nutrient cycling, it also limits the heat transfer efficiency of the soil, which can influence crop growth and soil temperature regulation.

Nevertheless, the presence of SOM in soil contributes to improved agricultural outcomes when managed optimally. Optimal λ levels can support healthy microbial communities that are essential for nutrient cycling and soil fertility (Xu et al. 2024a). Furthermore, SOM plays a key role in carbon sequestration, which is vital for mitigating the effects of climate change. While SOM generally reduces λ, it also helps the soil retain moisture, which can improve thermal stability by reducing rapid temperature fluctuations

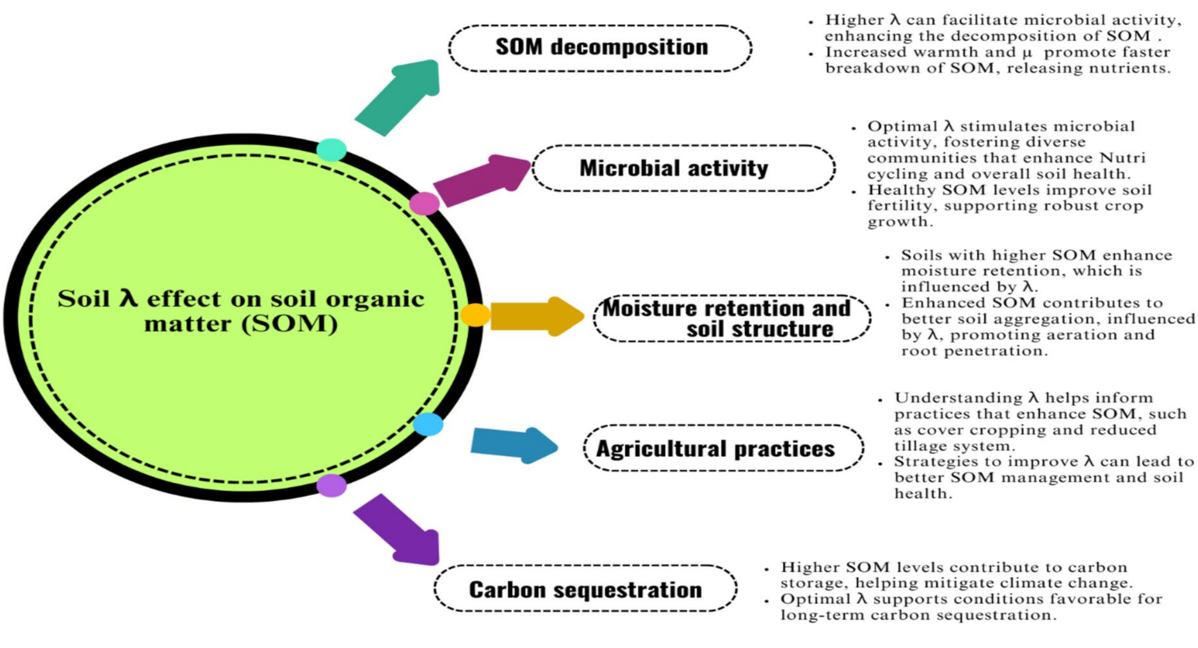

Fig. 4 Soil λ effect on soil organic matter (SOM) with its influence on environmental and agricultural processes

and maintaining more consistent conditions for plants and microbes.

The relationship between SOM and λ is also influenced by μ. As moisture content increases, λ tends to increase as well, since water has a much higher thermal conductivity than air (Abu-Hamdeh and Reeder 2000). However, when SOM content rises, the rate at which λ increases with moisture diminishes. This is due to the higher water retention capacity of organic matter, which holds more moisture but does not significantly improve the heat conductivity as much as the mineral components of the soil would (Xiuling et al. 2024).

The λ of soils rich in organic matter is further influenced by temperature. In frozen conditions, organic-rich soils typically exhibit higher λ due to the presence of ice, which conducts heat more efficiently than liquid water. However, as temperatures rise and the soil thaws, the moisture content in SOM-rich soils tends to decrease, which lowers λ. The porous and loose nature of organic matter also leads to increased air content within the soil matrix, further reducing heat transfer, since air is a poor conductor of heat (Wang et al. 2024c).

3.1.3 Irrigation practices (IP)

Irrigation practices (IP) play a critical role in influencing soil λ, and by extension, they affect key factors such as soil μ, soil temperature, root growth, and overall crop performance (Lunt et al. 2023; Parlak et al. 2022; Pascoal et al. 2024; Quan et al. 2024a; Tan et al. 2025). As depicted in Fig. 5, the interaction between IP and soil λ is essential for optimizing agricultural productivity and promoting soil health. The addition of water through irrigation increases the moisture content of the soil, which directly influences λ. Water, being a better conductor of heat than air, replaces air in soil pores, thereby enhancing the soil's ability to conduct heat (Fu et al. 2024a; Sepaskhah and Mazaheri-Tehrani 2024).

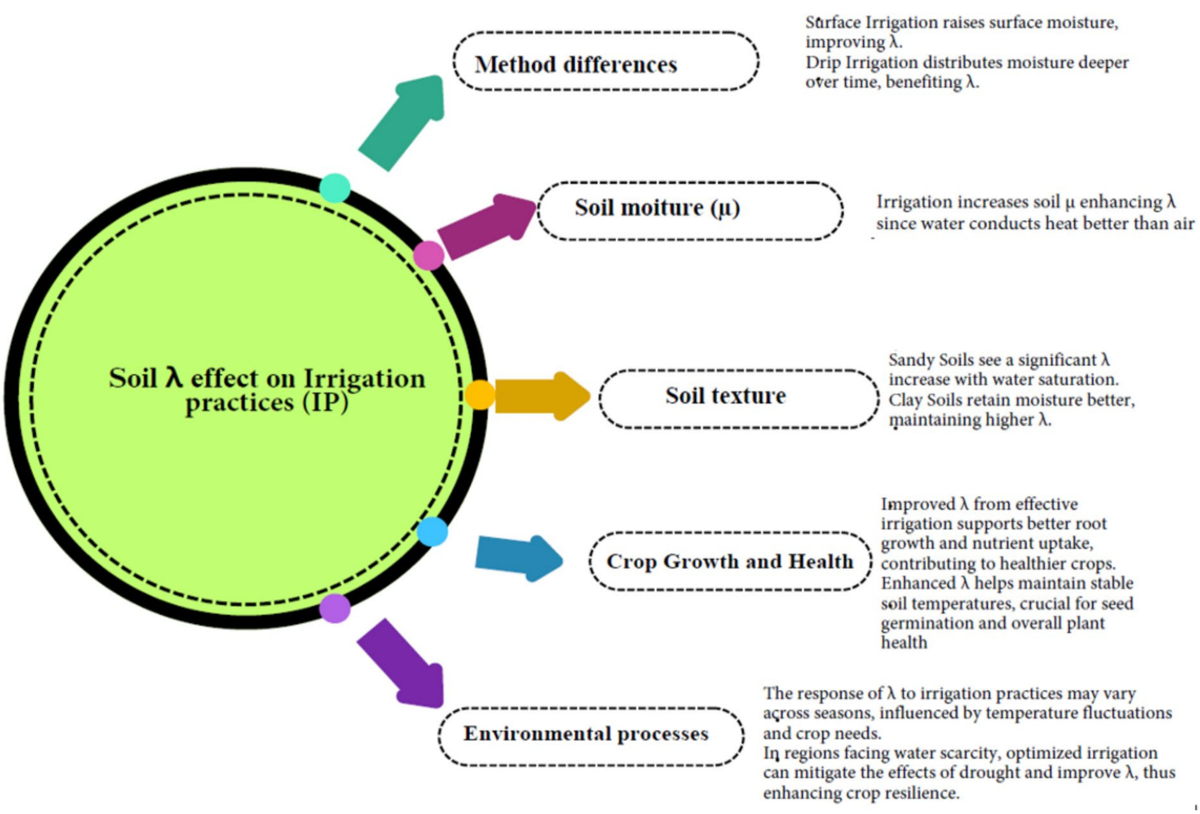

Fig. 5 Soil λ effect on irrigation practices (IP), with its influence on environmental and agricultural processes

This relationship is particularly evident in sandy soils, where water saturation can increase soil λ by orders of magnitude, given the significant contrast between water and air's thermal conductivity. Various irrigation methods, such as surface irrigation, sprinkler irrigation, and drip irrigation, impact soil temperature profiles in different ways. For example, surface irrigation tends to elevate soil moisture levels, which increases soil λ since water retains heat more efficiently than air (Fig. 5). The influx of water through surface irrigation leads to a more uniform distribution of moisture throughout the soil profile, thus improving λ.

In contrast, drip irrigation, which delivers water directly to the soil at specific points, can reduce surface soil temperatures and lower soil λ. The frequent, localized watering associated with drip irrigation generally results in lower moisture content in the surrounding soil areas, which reduces the overall heat retention ability of the soil (Wen et al. 2023). This decrease in λ can influence soil temperature dynamics, particularly at the surface, where heat fluctuations are more pronounced.

The effect of irrigation practices on soil λ is also affected by several extrinsic factors, including seasonal variations, soil type, climate conditions, and crop type (Parajuli et al. 2024; Pascoal et al. 2024). For instance, in dry conditions or during hot seasons, irrigation can significantly modify soil temperature profiles by enhancing moisture retention, which in turn improves λ and helps to moderate extreme temperature variations that could otherwise stress crops. Conversely, during cooler seasons or in regions with high rainfall, irrigation might have less of an effect on λ, as soil moisture levels are typically already high.

Given these factors, understanding the interactions between irrigation practices and soil λ is essential for farmers aiming to optimize irrigation methods. By carefully selecting and managing irrigation techniques, farmers can enhance soil health, as well as crop growth, and maximize water use efficiency. This, in turn, can lead to more sustainable agricultural practices, particularly in regions affected by water scarcity or erratic climatic conditions. Optimizing irrigation not only boosts λ but also contributes to better soil structure, more efficient nutrient cycling, and enhanced crop resilience to environmental stressors.

3.1.4 Crop rotation (CR)

Crop rotation (CR) is a key agricultural practice that can significantly influence soil λ, as shown in Fig. 6. CR enhances soil structure, increases organic matter content, improves moisture retention, and fosters the development of diverse root systems, all of which contribute to the stabilization of soil and its thermal properties. These changes ultimately benefit both crop growth and overall soil health (Haque et al. 2024; Haruna et al. 2017; Malek et al. 2021; Yang et al. 2024). Specifically, the inclusion of cover crops in CR systems can increase soil organic carbon (SOC), which is essential for controlling soil properties, including λ (Cerecetto et al. 2024).

While organic matter is known to generally reduce λ due to its effect on soil porosity, which decreases the packing density of soil particles (He et al. 2022; Zhu et al. 2019), the influence of CR on λ can be more complex. Higher levels of SOC contribute to the loosening of soil, leading to increased porosity, particularly in the upper layers. This can lower λ because the increased air-filled pore spaces hinder heat conduction. However, CR can also have an inverse effect on soil *pb*, which is typically negatively correlated with λ (He et al. 2021). For example, the practice of no-till cover crop management has been shown to increase pb compared to conventional tillage, which results in higher λ values (Haque et al. 2024; Saha et al. 2024).

Furthermore, CR can modify soil μ by influencing soil structure and organic matter content, which in turn affects water retention. As water has a higher thermal conductivity than air, increased moisture content generally leads to higher λ (Bayat et al. 2021). Cover crops, through their root systems and organic matter inputs, can also affect the distribution and size of soil pores. By increasing total pore space and water-filled pore spaces, cover crops help to increase moisture retention, thus promoting higher λ values (Schjønning 2021). However, the increase in organic matter may also lead to more air-filled pores, reducing λ due to air's relatively low thermal conductivity.

Understanding the effects of CR on soil λ is crucial for optimizing soil temperature regulation, which has a direct impact on crop development, microbial activity, and overall soil health. A reduction in λ, for instance, could help to mitigate extreme temperature fluctuations, which could be advantageous for crops that are sensitive to temperature stress. By carefully

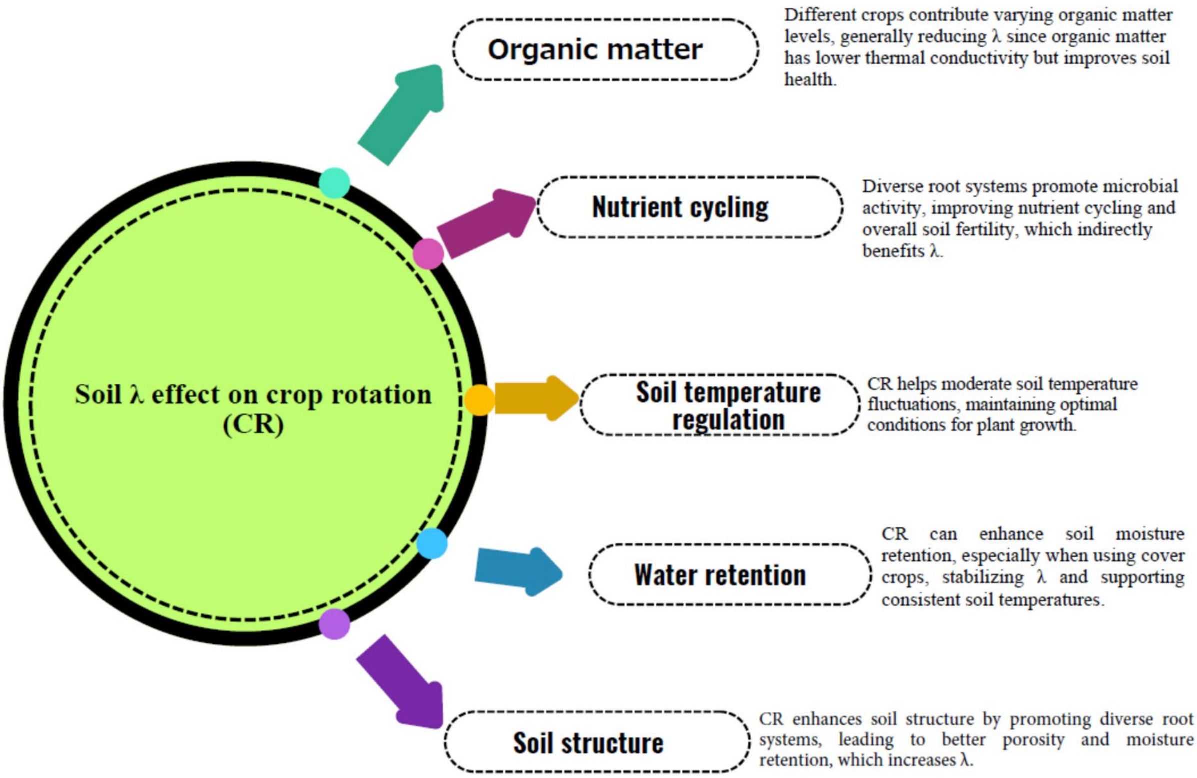

Fig. 6 Soil λ effect on crop rotation (CR), with its influence on environmental and agricultural processes

planning and implementing CR strategies, farmers can improve soil health, optimize water use, and increase crop productivity, leading to more sustainable agricultural practices and greater resilience to climate variability.

3.1.5 Nutrient availability (Nutri $_{av}$)

Soil λ has a profound impact on nutrient availability (Nutri $_{av}$) by influencing various factors such as soil temperature, μ, microbial activity, and root growth, which together govern the solubility and mobility of nutrients in the soil matrix (Al-Shammary et al. 2020a). As depicted in Fig. 7, these interconnected processes directly influence crop growth and yield by determining how nutrients are mobilized and accessed by plants.

Soil temperature is one of the most important factors affecting nutrient solubility and mobility. Temperature regulates the rate of chemical reactions and microbial processes, such as organic matter decomposition and nutrient mineralization. As soil temperature increases, microbial activity generally intensifies, leading to a higher Nutri $_{av}$. However, excessively high temperatures can cause the volatilization of specific nutrients, such as nitrogen, which reduces their bioavailability. Temperature fluctuations also influence root growth and exudation patterns, essential processes for nutrient uptake. Different plant species have optimal temperature ranges for growth, and deviations from these thresholds can impede nutrient absorption, leading to reduced plant health and growth.

The relationship between λ and μ is integral to nutrient transport within the soil. Higher λ is generally associated with higher moisture content, which enhances nutrient solubility and availability (Wu et al. 2025b). However, excessive moisture can lead to nutrient leaching, especially in systems where fertilizers are regularly applied, which could reduce the availability of essential nutrients. Soil texture further influences λ, and consequently Nutri $_{av}$. For example, sandy soils tend to have higher λ compared to clay-rich soils, but they also experience faster drainage,

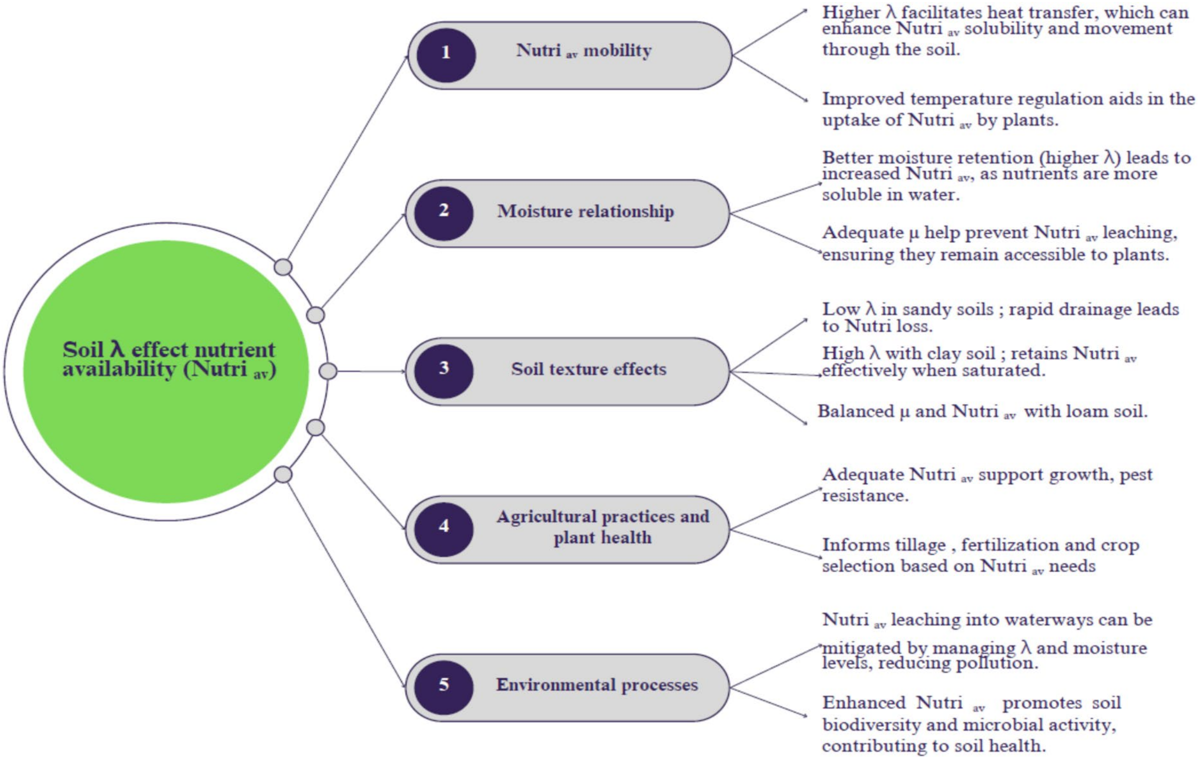

Fig. 7 Soil λ effect on nutrient availability (Nutri $_{av}$), with its influence on environmental and agricultural processes

which can result in reduced nutrient retention. On the other hand, clay soils have better moisture retention but lower λ, which can limit nutrient diffusion within the soil.

Agricultural practices such as tillage, irrigation, and crop spacing play a critical role in altering soil thermal behaviour, directly affecting nutrient availability. Conservation tillage and no-till farming practices, for instance, can improve soil λ by enhancing water retention and, subsequently, nutrient availability. These methods are particularly beneficial in comparison to conventional tillage systems, which may disrupt soil structure and reduce nutrient retention (Haque et al. 2024). However, soil compaction, which increases *pb*, can impede root growth while enhancing nutrient diffusion rates, which ultimately restricts nutrient uptake.

Organic matter (OM) content in soil is another critical determinant of both TCs and nutrient availability. While higher OM levels can improve nutrient retention, it can also lower λ, potentially slowing the rate at which nutrients are released. Soil pH and land management strategies are also vital factors influencing nutrient cycling and availability. For example, the use of organic amendments can significantly improve the soil's nutrient-holding capacity, but this may come at the cost of reduced λ due to the changes in soil structure that accompany organic matter buildup.

Given the complexity of these interactions, effective soil management requires a comprehensive understanding of how TCs, moisture dynamics, and nutrient availability are linked. Further research into the mechanisms by which TCs influence nutrient cycling is needed, particularly in light of changing climate conditions and the development of advanced agronomic technologies. A deeper understanding of these processes will be crucial for developing precision agriculture strategies that optimize nutrient use efficiency, ensuring both sustainable crop production and long-term soil fertility.

3.1.6 Soil textures (Soil $_{tex}$)

The texture of soil (Soil $_{tex}$) plays a significant role in determining its λ, with the characteristics of particle size, porosity, and water retention capacity having a profound influence (Klamerus-Iwan et al. 2024). These factors are crucial for understanding the behaviour of soils within agro-environmental systems, as soil texture directly impacts various soil properties that are essential for agricultural productivity and ecosystem health (Liu et al. 2024a; Różański 2022). As illustrated in Fig. 8, different soil textures, including sandy, silty, and clayey soils, exhibit distinct λ characteristics, largely due to differences in their particle size and μ (Song et al. 2024b; Xia et al. 2025).

Sandy soils, which are composed of large particles and have relatively large pore spaces, generally display low λ when dry. This is because air occupies the larger pores, which are less effective at conducting heat. However, when these soils are moistened, their λ increases sharply, as the water replaces the air in the pores. Water, being a better conductor of heat than air, significantly enhances the soil's ability to transfer heat. Therefore, sandy soils require frequent irrigation to maintain moisture and sustain their λ values, which is critical for managing soil temperature and ensuring crop growth.

On the other hand, clayey soils, with smaller particles and limited pore spaces, tend to have higher λ values. Even when dry, factors such as mineral composition, including iron oxide content, can influence the λ of these soils (Venegas et al. 2025). The small particle size and the strong interactions between the particles contribute to a higher capacity for water retention and heat conductivity. This characteristic makes clayey soils more efficient at conducting heat, though they are prone to issues like waterlogging if drainage is not managed properly. Therefore, it is essential to ensure proper drainage in clay-rich soils to avoid excess water retention, which could negatively impact plant health and soil structure.

Loamy and silty soils, with a more balanced mixture of particle sizes, generally provide moderate λ values. These soils offer steadier λ, making them ideal for agricultural systems. Their balanced texture allows for a mix of water retention and drainage, which helps maintain optimal soil temperature and moisture conditions for crop growth (Wessolek et al. 2023). Loamy soils, in particular, are considered highly productive due to their ability to retain adequate moisture while allowing excess water to drain away, creating favourable conditions for both root growth and nutrient availability.

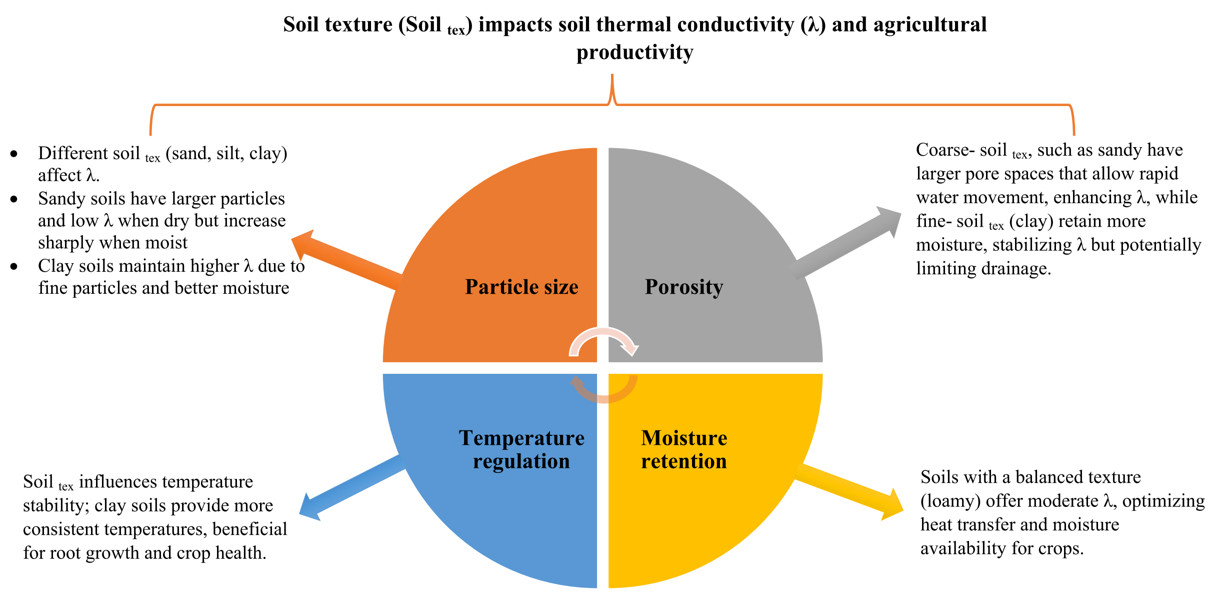

Fig. 8 Soil λ effect on soil texture (Soil $_{tex}$), with its influence on environmental and agricultural processes

3.1.7 Soil mineral content

Soil mineral composition plays a crucial role in determining its λ, a relationship that is influenced by a variety of factors such as weathering processes, moisture retention, microbial activity, and other soil properties like Φ, *ρb*, and OM content (Al-Shammary et al. 2020b; Chen et al. 2020; Kolawole et al. 2024; Li et al. 2021; Wu et al. 2025b). As illustrated in Fig. 9, the mineral content in soil affects its overall TCs through its impact on soil structure, aggregation, and the interaction between particles, which in turn influences heat transfer.

Soils with well-structured particles typically have higher λ values. This is because stable soil aggregates create larger pore spaces, which facilitate heat transfer more effectively (Chen et al. 2020). In contrast, soils with poor structure and excessive compaction tend to have lower λ values, as the smaller pore spaces and reduced pore connectivity hinder heat flow. Minerals such as quartz are particularly influential in this regard, as they have a high λ compared to other minerals. As a result, soils with higher quartz content tend to have elevated λ (Lunt et al. 2023; Tarnawski et al. 2022; Wu et al. 2025b; Ye et al. 2022). The presence of iron oxides, which are highly conductive, further enhances soil λ by improving heat transfer (Venegas et al. 2025).

The mineral composition of soils also influences moisture retention, which in turn affects λ. For example, clay-rich soils retain more moisture than sandy soils, and water's high specific heat capacity increases λ in such conditions (Yuan et al. 2021). The presence of minerals like feldspar and pyroxene can alter thermal conductivity in various ways, as some minerals increase heat transfer while others reduce it (Venegas et al. 2025). These variations emphasize the need for advanced modelling techniques to accurately predict soil λ, taking into account the diverse mineral compositions and their thermal behaviours (Li et al. 2021).

Porosity also plays an inverse role in soil λ. As soil Φ increases, λ typically decreases. This occurs because air, which occupies the larger pore spaces, is a poor conductor of heat. As a result, soils with higher Φ, such as sandy soils, often exhibit lower λ when dry but show a significant increase in λ when moisture is present, as water replaces the air in the pores (Abu-Hamdeh and Reeder 2000; Venegas et al. 2025). Conversely, clay soils, which have smaller particles and less pore space, are more efficient at retaining moisture and have a unique

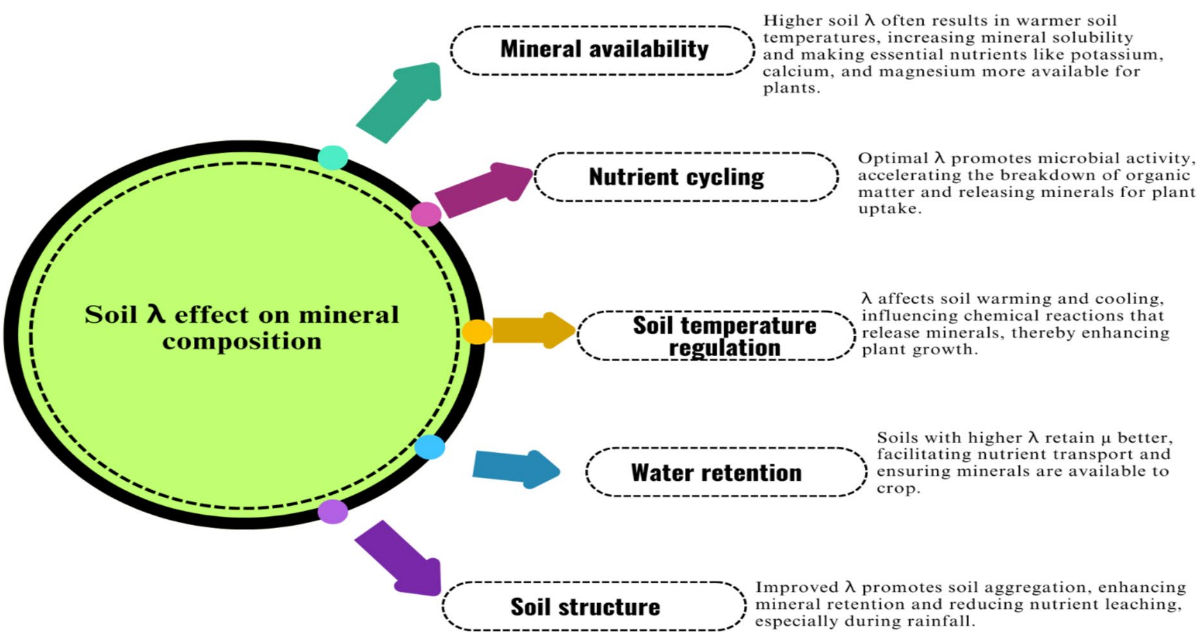

Fig. 9 Soil λ effect on mineral content with its influence on environmental and agricultural processes

thermal profile that is distinct from sandy soils (Ihekweme et al. 2020; Venegas et al. 2025).

In addition to moisture content, the interaction between OM and soil minerals also affects λ. Organic matter enhances soil structure and moisture retention, but it generally lowers λ compared to the mineral components of the soil. This is because OM has lower λ compared to the mineral aggregates in the soil (Venegas et al. 2025). Furthermore, temperature variations can induce chemical and physical changes in minerals, which in turn modify their λ properties. For example, in frozen conditions, ice—having a higher thermal conductivity than liquid water—can enhance the overall λ of the soil. However, once the soil thaws, increased air content reduces λ (Lei et al. 2023).

Recent advancements in machine learning have greatly improved the prediction of soil λ by integrating diverse parameters, including mineral composition. Techniques such as ensemble machine learning and artificial neural networks (ANN) have been shown to outperform traditional empirical models, providing more accurate and precise predictions of soil λ (Li et al. 2021). These data-driven approaches allow for more informed decisions in agricultural and engineering applications, as they incorporate mineral composition, porosity, and moisture content into predictive models.

For farmers, understanding the influence of soil mineral composition on soil λ is essential for making informed decisions regarding soil management. By leveraging advanced modelling techniques and integrating data on soil properties, farmers can optimize irrigation, nutrient management, and land-use practices to improve agricultural productivity and ensure sustainable soil health.

3.1.8 Soil temperature regime ($T_{soil\ reg}$)

The Soil Temperature Regime and its relationship with soil λ are crucial for understanding heat transfer processes within soils, directly influencing crop and soil management practices in agricultural systems. As illustrated in Fig. 10, the interplay between λ, temperature, and soil μ is well-documented. Soil λ tends

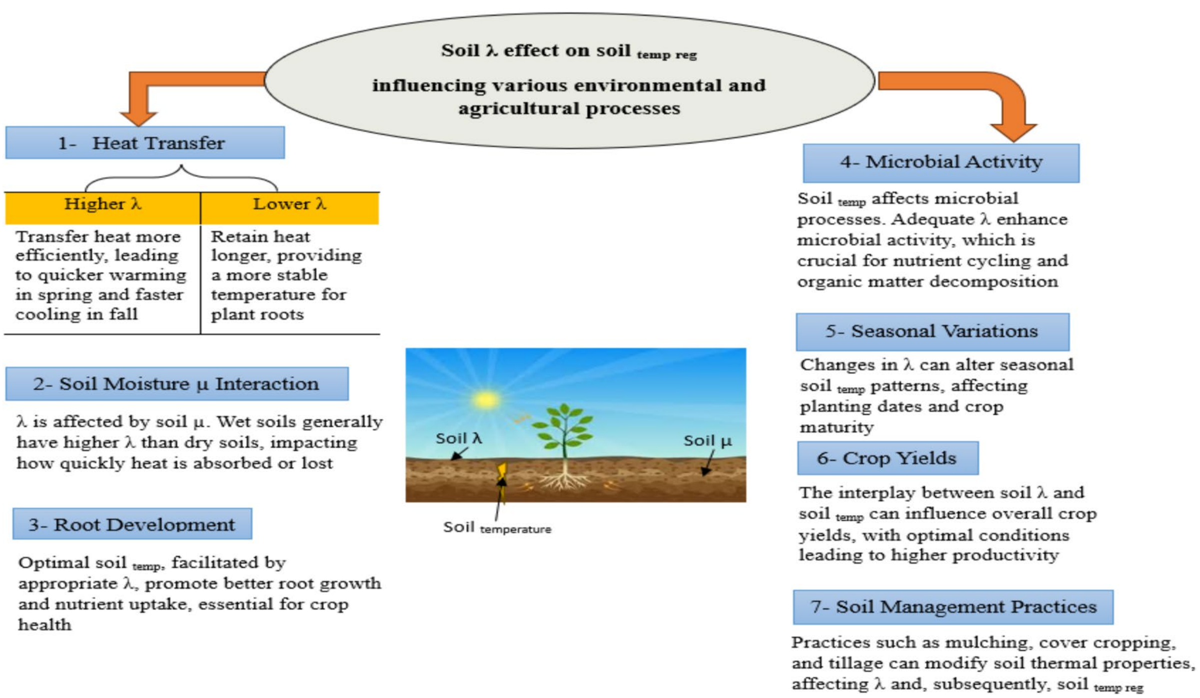

Fig. 10 This figure illustrates the effect of λ on soil temperature regimes (Soil $_{temp\ reg}$) and its resulting influence on various environmental and agricultural processes. It highlights how different soil management practices (SMP) and climate adaptation strategies (CAS) impact soil temperature stability, thereby affecting plant growth, microbial activity, and nutrient availability

to increase as temperature rises, especially in conditions where the soil's water content is high (Kňažková and Hrbáček 2024; Wang et al. 2024a; Wessolek et al. 2023). The soil temperature is closely linked to air temperature, with long-term trends in air temperature closely correlated to annual soil temperature averages (Zhang et al. 2023).

$T_{soil\ reg}$ play a pivotal role in several essential ecosystem processes, including water evaporation and plant transpiration. These processes are critical for maintaining agricultural productivity and ecological balance (Tai et al. 2024). As temperatures rise, the rate of water evaporation and plant transpiration typically increases, affecting moisture availability and crop health. Global models predict $T_{soil\ reg}$ using pedotransfer functions, which relate soil texture and *pb* to TCs (Pan et al. 2024). However, there are significant local variations in λ, resulting in different temperature regimes across various soil types (Fig. 10).

The soil λ significantly influences the thermal regime, which is vital for seed germination (He et al. 2020), root growth, and the overall development of plants. An optimal $T_{soil\ reg}$ fosters healthy microbial activity, which is essential for nutrient cycling and organic matter decomposition. This underscores the importance of managing soil thermal conditions to support plant growth and productivity.

While the intrinsic TCs of soil are essential, other external factors, such as mulching (Mari et al. 2024), cover cropping (Khan et al. 2018), tillage practices (Lozano-Parra et al. 2023; Yin et al. 2023), and broader factors like climate change and land use changes (Abu El-Magd et al. 2024; Paramesha et al. 2025), also significantly influence the soil temperature regime. These practices can directly alter the soil's moisture levels and, consequently, its λ. For instance, mulching can help regulate soil temperature by providing insulation, reducing temperature extremes, and improving moisture retention. Similarly, cover cropping and conservation tillage practices can influence the soil's thermal dynamics by modifying its surface structure, moisture content, and organic matter levels.

These external factors must be carefully considered when developing soil management strategies, as they all contribute to variations in soil thermal behaviour. Understanding the complex interactions between soil properties, temperature, and external management practices is essential for optimizing $T_{soil\ reg}$. Effective soil management can ensure a more sustainable agricultural system by improving soil health, fostering microbial activity, and enhancing crop growth through more favourable temperature conditions. With ongoing changes in climate and land use patterns, adapting these strategies will be increasingly crucial for ensuring long-term agricultural productivity and ecological sustainability.

3.1.9 Soil water movement and retention

The relationship between soil λ and soil μ is fundamental in determining water movement and retention within the soil profile. This interaction directly influences several environmental and agricultural processes, as illustrated in Fig. 11. As moisture content increases, λ typically rises, primarily because water has a higher heat capacity than air (Wang et al. 2024a; Wu et al. 2025b). This enhanced heat conduction capacity significantly improves the soil's ability to transfer heat, which stabilizes the thermal profile and is crucial for promoting agricultural productivity (Kolawole et al. 2024).

When soils are more saturated, the heat distribution becomes more uniform due to the greater presence of water, which facilitates effective thermal transfer. This leads to a more stable soil temperature regime, which is particularly beneficial for the development of crops. On the other hand, when the moisture content is low, λ decreases as air-filled pores become more prominent, leading to higher temperature fluctuations within the soil profile (Khaledi et al. 2023; Liu et al. 2023). This reduced stability in temperature can negatively impact crop health, as plant roots are sensitive to extreme temperature variations.

The impact of λ on water movement and retention is not uniform across different soil types. Sandy soils, characterized by their large particles and high porosity, drain water quickly and generally have a lower μ. Consequently, their λ is reduced, making them prone to rapid heating and cooling, which contributes to unstable temperature conditions (Fig. 11). This variability in temperature makes sandy soils less suited for crops that require consistent thermal conditions.

In contrast, clayey soils have a dense particle structure and a high water retention capacity, which leads to higher λ when saturated. The enhanced water retention capacity contributes to a more stable temperature profile, making clayey soils more favourable

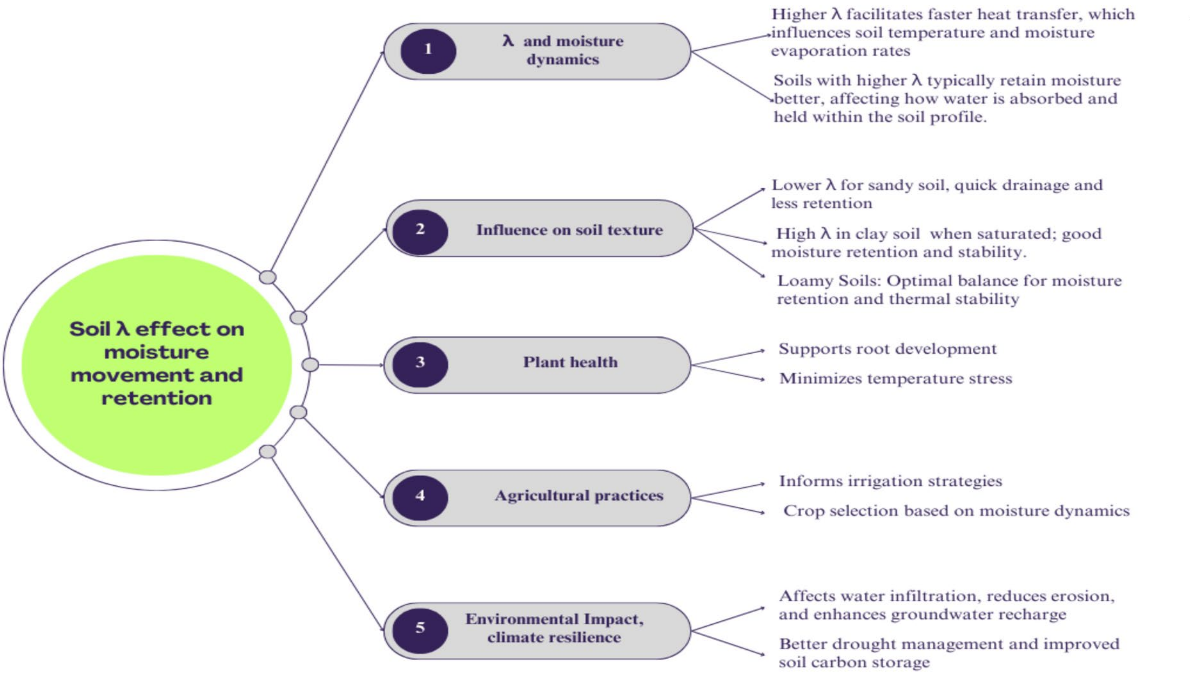

Fig. 11 Soil λ effect on moisture movement and retention, with its influence on environmental and agricultural processes

for crops that thrive under consistent thermal conditions (Vu et al. 2023). Loamy soils, which offer a balance between water retention and aeration, create a stable thermal environment, supporting healthy root development and overall plant growth. Their ability to maintain a stable temperature profile, combined with their water retention capacity, makes them optimal for agricultural use.

Dry soils, on the other hand, are characterized by lower λ values and greater temperature variability. This lack of moisture leads to more pronounced temperature fluctuations, which can have detrimental effects on plant health and agricultural productivity.

Understanding the relationship between λ, water movement, and retention is critical for optimizing agricultural practices. This knowledge provides farmers and agronomists with the tools to: (1) Optimize IP by understanding soil μ characteristics, irrigation schedules can be tailored to maximize water infiltration and retention, reducing water waste and ensuring adequate plant water availability (Ernest et al. 2024); (2) Improve drought resilience, as a deeper understanding of how λ dynamics operate under low-moisture conditions can help develop strategies to manage soil more effectively during drought, ensuring better moisture utilization (Al-Shammary et al. 2020a); and (3) Select suitable crops using the knowledge on how specific λ and μ profiles of soils can guide the selection of crops best suited to the thermal and moisture conditions of the soil, enhancing yield potential and optimizing land use.

3.1.10 Soil structure and health

Soil λ impacts soil structure and health, as shown in Fig. 12. Soil structure refers to the arrangement of soil particles and pores, which directly determines soil functionality and its thermal behaviour (Haque et al. 2024; Wu et al. 2025a). The interaction between soil structure and λ affects key soil processes such as water retention, temperature regulation, and heat transfer, which in turn influences plant growth, microbial activity, and water dynamics within the soil (Xu et al. 2024b).

Several factors contribute to variations in soil λ, with soil μ being the most influential. When soil moisture increases, water replaces air in the soil pores, which significantly enhances heat transfer. This effect can often result in a substantial increase in λ (Wu et al. 2025b). This relationship varies across

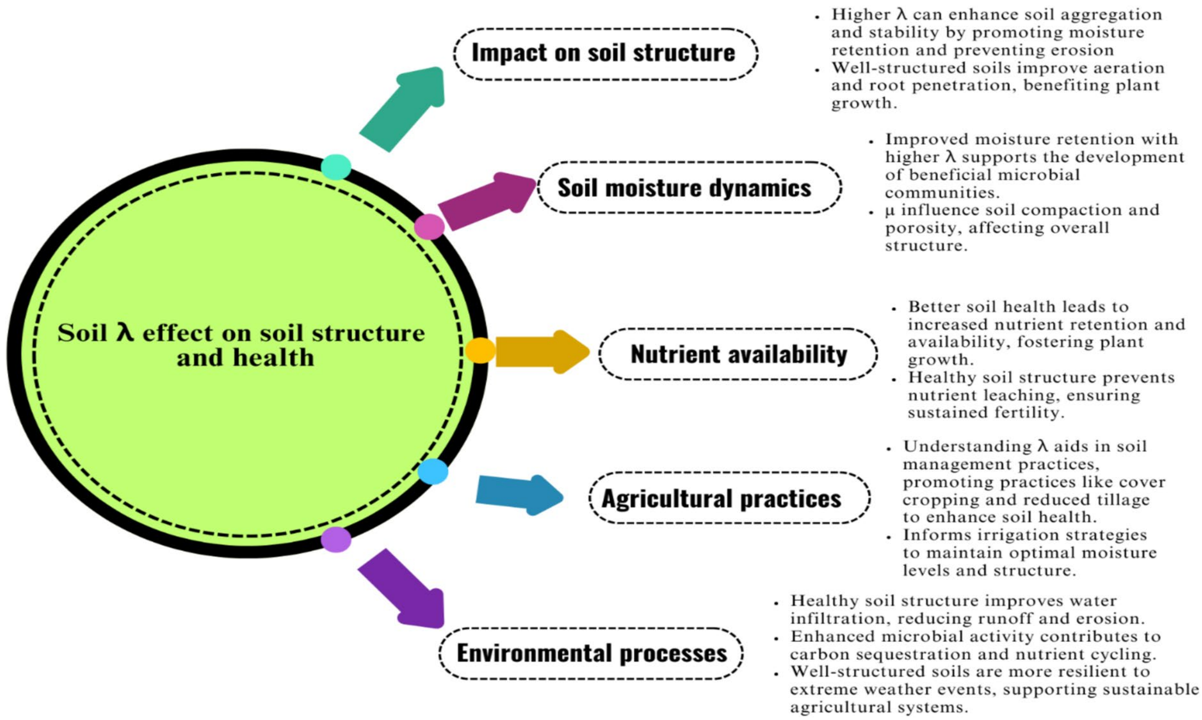

Fig. 12 Soil λ effects on soil structure and health, with its influence on environmental and agricultural processes

different soil types, as soil texture, *pb*, and composition also play significant roles in determining the TCs of the soil (Liu et al. 2024b; Lunt et al. 2023; Tian et al. 2025).

Soil aggregation has a particularly important role in soil λ. Non-aggregated soils, which tend to have less organized particle arrangements, typically exhibit higher λ due to improved particle-to-particle contact and better bridging of pore water. On the other hand, well-aggregated soils, with their complex pore structures, often have lower λ values. The presence of intra-aggregate pores impedes the movement of heat, leading to reduced thermal conductivity. Additionally, the texture of the soil also contributes to the variability of λ, with coarse-textured soils (like sand) generally having higher λ than fine-textured soils (like clay). These differences have practical implications for soil productivity and its capacity to support agricultural activities (Fig. 12).

The influence of *pb* on λ is notable. Soils with higher pb generally have fewer air gaps, facilitating better heat transfer and resulting in higher λ values. Conversely, soils with lower *pb*, often found in more porous or loamy soils, can exhibit reduced λ due to the larger air-filled spaces, which are poor conductors of heat. In clayey soils, for example, the increased presence of micro-pores can reduce λ, as these micro-pores impede the efficient flow of heat through the soil matrix.

An optimal soil structure supports improved TCs, contributing to healthier soils and more resilient crops. One of the most significant impacts of λ on soil health is its effect on the soil microclimate, especially during early plant growth and development. A stable root-zone temperature, influenced by λ, is critical for seedling growth and establishing strong root systems. Additionally, the role of soil TCs extends beyond plant growth; they are also essential for maintaining microbial activity and biodiversity in the soil, which is crucial for nutrient cycling and organic matter decomposition.

Understanding these interactions between soil structure, thermal conductivity, and soil health can guide soil management practices aimed at optimizing λ. Such practices could include adjusting irrigation techniques to modify soil moisture levels, implementing tillage methods that influence soil aggregation, and selecting crops suitable for the specific thermal and moisture conditions of the soil.

Future research should focus on how changing climate conditions and land use practices may affect the relationship between λ and soil structure. Advances in soil monitoring technologies, such as fiber-optic sensing and machine learning-based predictive models, could significantly enhance our ability to monitor and manage soil TCs. These technological innovations will improve the precision of soil management strategies and contribute to better agricultural outcomes, promoting sustainable soil health and long-term productivity.

3.2 Influence of climate adaptation strategies (CAS) on soil thermal conductivity (λ)

3.2.1 Soil mulching (SM)

Soil mulching (SM) plays a pivotal role in regulating soil λ, as illustrated in Fig. 13. The impact of different mulching materials and environmental conditions on the heat transfer characteristics of agricultural soils across varying climates warrants a detailed study (Zhao et al. 2024). Both organic and inorganic mulches significantly influence TCs by altering heat and moisture dynamics, thereby affecting λ, which in turn has substantial implications for agricultural productivity and soil sustainability.

Soil λ in mulched soils is influenced by several key factors, including the type of mulch used, its specific properties, soil μ, and prevailing weather conditions. The application of mulch acts as an insulating layer, reducing the exchange of heat between the soil and the surrounding atmosphere. This modification of the thermal regime of the soil is crucial for optimizing plant growth and soil health.

Organic mulches (Mulches $_{org}$) such as straw, wood chips, and leaves are commonly utilized due to their low λ. Their porous and air-filled structures provide an insulating effect that stabilizes soil temperatures (Iacuzzi et al. 2024; Visconti et al. 2024). The reduced heat transfer associated with these materials helps mitigate extreme temperature fluctuations, benefiting plant roots by maintaining a more consistent soil temperature. This temperature

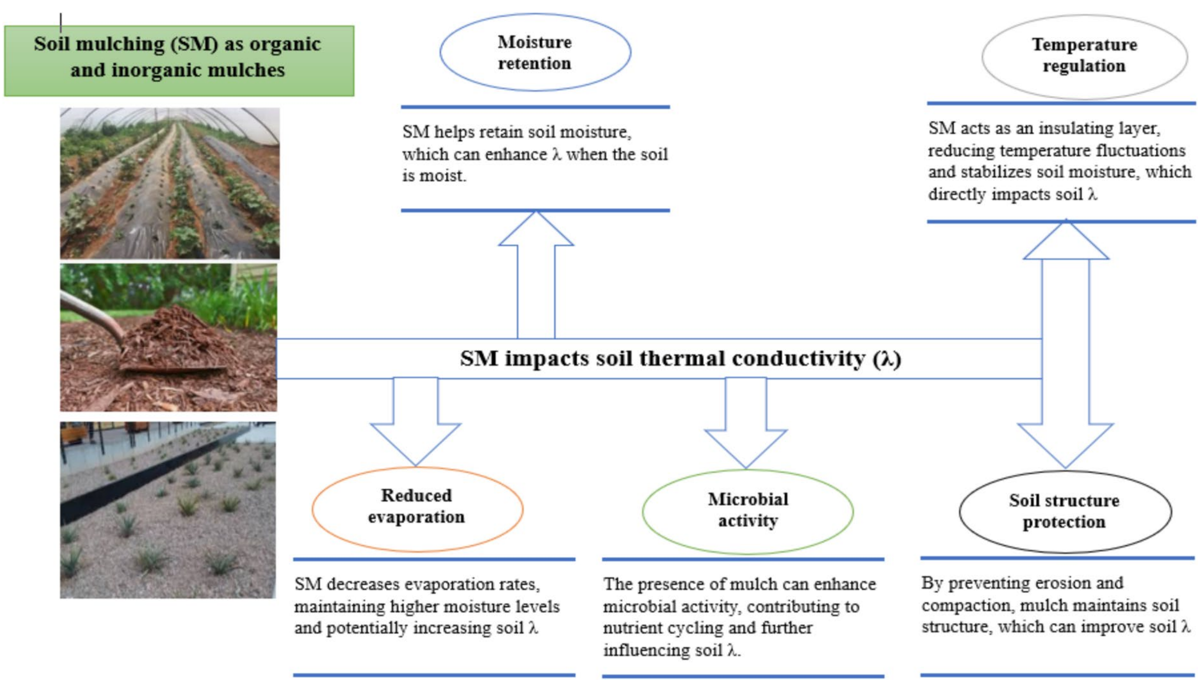

Fig. 13 Soil mulching (SM) impacts soil λ: This figure demonstrates how mulching practices enhance soil moisture retention, regulate temperature, protect soil structure, support microbial activity, and reduce evaporation, ultimately improving overall soil health by providing an insulating layer that contributes to better crop performance and increased resilience to climate variability

regulation is especially beneficial in regions with significant temperature variability, where crops can suffer from thermal stress.

On the other hand, inorganic mulches (Mulches $_{inorg}$), such as plastic covers or gravel, can have a different effect on λ. These materials often possess higher thermal conductivity due to their dense composition, leading to increased heat transfer into the soil. For instance, plastic films, especially black and semi-transparent varieties, can significantly raise soil temperatures, which may be beneficial for crop growth in cooler climates or during cooler seasons (Chu et al. 2022; Kang et al. 2024; Li et al. 2023). This ability to trap heat within the soil can help speed up germination and promote growth in conditions where the soil temperature is suboptimal for plant development.

Conversely, Mulches $_{org}$ such as straw or grass clippings, which are particularly effective in warmer climates, can lower the soil temperature. This is beneficial in hot regions where excessive heat can cause moisture stress or damage sensitive crops. The cooling effect of Mulches $_{org}$ helps to maintain a more favourable microclimate for root growth and microbial activity by reducing heat buildup in the soil.

Mulching materials also affect the soil's heat storage capacity. For example, black plastic mulch, while increasing soil temperature, may optimize heat retention, which helps create a stable soil environment conducive to microbial activity and plant growth (Chen et al. 2024b). This stability, in turn, influences the λ of the soil by fostering a more uniform thermal profile. Additionally, mulching enhances the moisture retention capacity of the soil, which further contributes to temperature stability and promotes optimal conditions for root and microbial development.

By understanding how different mulching materials and strategies interact with TCs, farmers and land managers can make informed decisions about mulching practices to optimize soil conditions. For example, selecting appropriate mulch types for specific climates can improve temperature regulation, conserve moisture, and protect the soil from erosion, all of which contribute to better crop yields and more sustainable land management practices.

3.2.2 Climate change

Soil λ significantly influences climate change by affecting heat flow density, precipitation patterns, and soil temperature dynamics (Guo et al. 2024; Pan et al. 2024; Roghangar and Hayley 2024). As illustrated in Fig. 14, understanding the role of λ within the broader land–atmosphere interaction framework is crucial. Soil μ, OM, and land cover are additional key factors that mediate these processes.

Variations in λ can introduce errors in surface energy balance (SEB) (Wang et al. 2022b), ultimately impacting local and regional climate conditions. The SEB is critical in regulating the energy exchange between the soil and the atmosphere, and deviations in λ can cause inaccuracies in predicting sensible and latent heat fluxes. These discrepancies are particularly pronounced during wet and dry cycles (Formigari and Tsuha, 2025), leading to miscalculations in climate modelling and forecasting.

Soil λ plays a significant role in precipitation simulation. Changes in λ affect surface temperatures, which in turn alter processes and rainfall patterns. Elevated λ values can contribute to increased surface temperatures, potentially reducing precipitation. This relationship underscores the necessity of integrating accurate λ measurements into climate models to improve predictions of rainfall variability and regional climate shifts.

The impact of soil λ extends beyond temperature regulation; it is crucial for microbial and abiotic processes that influence crop growth, nutrient leaching, and greenhouse gas emissions. For example, the correlation between soil water saturation and λ governs heat transfer rates and soil temperature stability, both of which are essential for ecosystem services (Kolawole et al. 2024).. Furthermore, variations in λ affect soil respiration rates and microbial activity, influencing the release of carbon dioxide (CO_2) and methane (CH_4), key contributors to climate change.

While soil λ is an essential factor in climate variability, it is also highly susceptible to overarching climatic elements. Seasonal fluctuations, extreme weather events, and long-term shifts in climate patterns can obscure its direct effects on climate systems. Prolonged droughts, increased precipitation variability, and temperature extremes can alter soil λ, creating feedback loops that further complicate climate predictions.

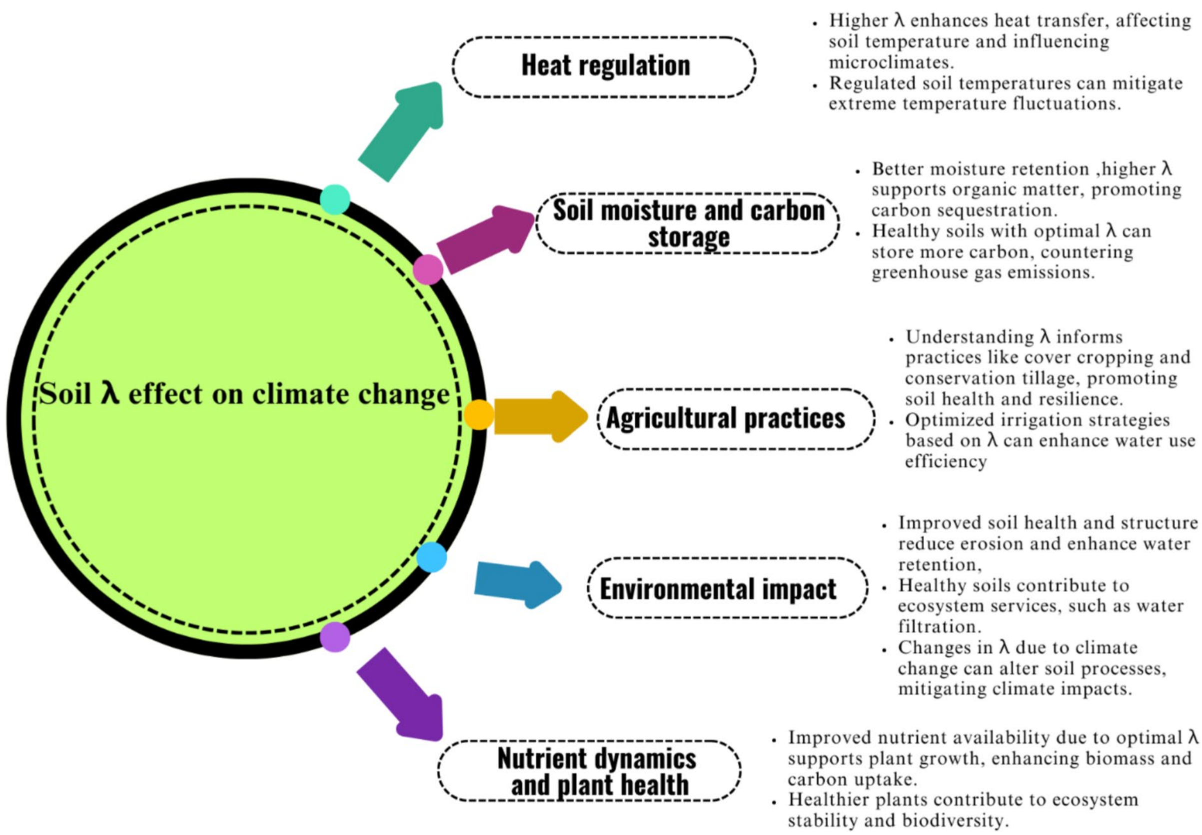

Fig. 14 Soil λ effect on climate change, with its influence on environmental and agricultural processes

3.2.3 Precision agriculture (agriculture $_{prec}$)

Precision agriculture (Agriculture $_{prec}$) is significantly influenced by soil λ, as it impacts critical factors such as crop microclimates, irrigation control, and nutrient availability (Lei et al. 2023; Wu et al. 2025b). Figure 15 illustrates the role of soil λ in precision agriculture, emphasizing its profound effects on environmental and agricultural processes. Understanding and controlling soil λ is key to optimizing agricultural practices, improving crop growth, and ensuring sustainability.

Soil λ plays a critical role in regulating the crop microclimate, which directly affects seed germination and early plant growth. These processes are heavily influenced by the soil temperature regime and μ, both of which are directly impacted by λ. An increase in soil λ is typically associated with higher μ and *pb*, which enhances heat retention and stabilizes soil temperatures, creating favourable microclimates for crops (Al-Shammary et al. 2022; Wu et al. 2025b). This is especially important for optimizing planting strategies, as soil λ influences the availability of heat in the root zone, which in turn affects plant metabolism and early-stage development.

In precision agriculture, understanding the relationship between soil λ and soil moisture is essential for efficient irrigation management. By controlling TCs, farmers can optimize irrigation scheduling, ensuring that water is used efficiently and retained in the soil for longer periods. This helps minimize losses due to evaporation and runoff, which is especially important in regions with water scarcity. Proper irrigation management based on soil λ improves water use efficiency, helping to conserve water and support sustainable farming practices.

Soil λ also has a direct impact on microbial activity and nutrient diffusion in the soil, both of which are essential for nutrient cycling, such as nitrogen availability and plant uptake (Shah et al. 2024a,

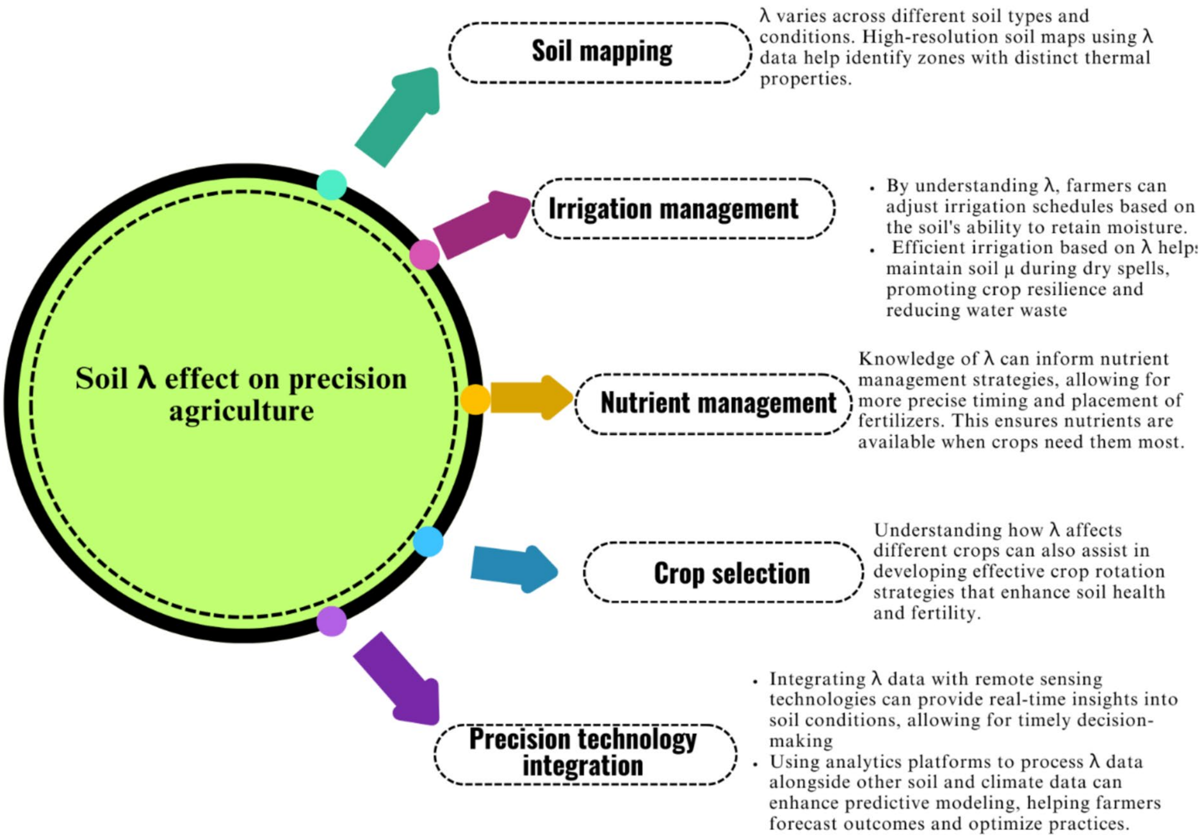

Fig. 15 Soil λ effect on precision agriculture with its influence on environmental and agricultural processes

2024b). Higher λ can facilitate microbial processes that break down organic matter, releasing essential nutrients into the soil for plant uptake. Increased λ also improves nutrient availability by facilitating better nutrient diffusion, leading to more efficient fertilizer absorption and, ultimately, higher crop yields. However, excessive λ may increase nutrient depletion or volatilization in certain conditions, which necessitates careful management to prevent nutrient loss.

While a higher soil λ can support plant growth by improving heat and moisture distribution, it can also lead to increased evaporation rates, which may cause water loss that could negatively affect crops, particularly in dry conditions. Therefore, precision agriculture requires a delicate balance between managing soil TCs and implementing water conservation strategies to ensure that soil conditions remain optimal for crop growth without excessive water loss.

4 Discussion and limitations

Soil λ plays a pivotal role in agro-environmental systems (A-ES) by influencing physical, chemical, and biological processes within the soil. These processes are impacted by SMP and CAS, as outlined in the following sections.

4.1 Soil management practices (SMP) influence on soil thermal conductivity

Key soil management practices (SMP) influence soil λ through various mechanisms, including Ts, SOM management, IP, CR, Nutrient $_{av}$, soil textures, soil mineral content, $T_{soil\ reg}$, soil water movement and retention, and soil structure as presented in Table 1. For example, soil λ is a crucial factor in determining the effectiveness of tillage practices, as it impacts heat transfer, soil temperature, water retention, and plant growth. The relationship between soil λ and Ts

Table 1 Summary of the impact of soil management practices (SMP) on soil thermal conductivity (λ)

Soil management practices (SMP) ID	Impact on λ	Examples/mechanism
Tillage systems	Conventional tillage increases λ	Reduces bulk density (*ρb*), increases porosity (Φ), enhancing heat transfer
	Conservation tillage stabilizes λ	Preserves soil structure, retains moisture, and maintains soil organic matter (SOM)
Soil organic matter (SOM)	Incorporation of organic matter decreases λ but improves moisture retention	OM of soil has lower thermal conductivity than minerals; increases Φ
Irrigation practices	Increases soil moisture (μ), enhances λ	Surface irrigation, drip irrigation
Crop rotation	Influences soil structure and SOM, affects λ	Diverse crop rotations and inclusion of cover crops, lead to enhances organic matter, soil aggregation, and pore diversity
Nutrient availability	Influences plant growth and health, indirectly affects λ by linked to OM of soil, μ, soil pH	Soil amendments and fertilizer application lead to enhances Nutri $_{av}$ but may slow heat transfer, requiring balanced OM management
Soil textures (Soil tex)	Impact on moisture retention and λ	Sandy texture has large pores fill with water (high λ); low λ when dry. Clayey texture has small pores retain water, improving heat transfer; high mineral content. Loamy soil has moderate λ, because balanced sand, silt, and clay mixture retains μ and heat effectively
Soil temperature regime	Impacts λ through temperature variations	Seasonal changes, diurnal temperature fluctuations
Soil water movement and retention	Directly impact on λ; higher moisture typically increases λ	Saturated vs. dry conditions
Soil structure and health	Influences moisture retention, temperature regulation, and λ	Well aggregated vs. compacted soils

is complex and influenced by various soil properties and environmental factors. Ts practices can alter soil structure, which in turn affects λ and water distribution. Tillage $_{trad}$ typically increases λ by reducing bulk density and increasing porosity, facilitating heat flow (Al-Shammary et al. 2022; Wang et al. 2023c). This agrees with Ball et al. (2025), who noted that Tillage $_{trad}$ affects λ by inducing structural changes, altering moisture content, and causing compaction effects. Some studies (e.g., Thotakuri et al. 2024) found that excessive Tillage $_{trad}$ can disrupt soil moisture continuity, reducing λ in arid regions. In contrast, Tillage $_{cons}$ maintains a more stable soil structure, increasing moisture retention while decreasing thermal diffusivity.

Soil λ also varies with depth due to changes in soil properties. Deeper soil layers typically exhibit lower λ because of compaction and reduced porosity (Al-Shammary et al. 2022; Thotakuri et al. 2024). Overall, tillage depth effects are soil-specific: sandy soils benefit from shallow tillage, clayey soils from deep (Li et al. 2024). Tillage practices influence soil temperature profiles by altering surface exposure and insulation, particularly in shallow tillage systems. This is contrary to Thotakuri et al. (2024), who observed that Ts affects soil λ by altering soil structure and pore geometry, which, in turn, influences heat transfer via convection along the soil depth. No-till (NT) systems can lower soil temperature and λ due to the surface residue cover that acts as an insulator. However, long-term effects of Ts on soil health under various climatic conditions remain insufficiently investigated, and results vary across different soil types and regions.

Soil management practices affect λ by influencing soil structure and moisture retention. High levels of SOM typically reduce λ because organic matter has a lower λ compared to mineral components (He et al. 2021; Wu et al. 2025b). SOM increases soil porosity and moisture retention, thereby boosting microbial activity and nutrient cycling. However, when soils remain saturated, this relationship becomes more complex, as increased water content can elevate λ due to water's higher λ. Xiuling et al. (2024) discussed that the general factors affecting soil λ, such as moisture content, porosity, and degree of saturation, can influence λ in various soils. Additionally, saturated SOM-rich soils may have different λ due to the insulating properties of organic matter, which can affect heat transfer compared to mineral soils. Effective SOM management not only improves soil health and fertility but also regulates soil TCs, which are crucial for optimizing crop production and resilience to climate variability. Understanding these dynamics is essential for developing sustainable SMP that balance thermal performance with other indicators of soil health.

For IP, the elevation of λ is a result of increased μ, which enhances the soil's ability to conduct heat. Since water has much higher thermal conductivity than air, irrigation practices that replace air in soil pores with water significantly boost λ. The method of irrigation is also an essential factor in this relationship. For instance, surface irrigation typically maintains higher soil moisture levels, thereby increasing λ. On the other hand, methods like drip irrigation may initially lower surface moisture levels but can improve moisture distribution in the soil profile over time, ultimately affecting λ positively. Optimizing IP is critical for managing soil TCs and improving agricultural productivity, particularly in regions with water scarcity and climate variability (Parajuli et al. 2024). Understanding these interactions allows farmers to better manage irrigation practices to achieve sustainable outcomes in crop production.

Crop rotation (CR) enhances soil structure and organic matter content, which may lead to a reduction in λ by fostering the growth of different root systems and improving soil aggregation (Haruna et al. 2023). CR, especially with cover crops, can affect soil λ by modifying soil structure and organic matter content. Tillage interaction with CR's effects on λ depending on whether it's paired with Tillage $_{cons}$ (Haque et al. 2024). Different crops contribute various types and quantities of organic matter to the soil, enhancing overall SOM content. Higher SOM levels generally decrease λ because organic matter has a lower λ. However, complex interactions, such as those involving soil texture, climatic conditions, and management practices, also influence this relationship (Jarrah et al. 2022; Mendis et al. 2022; Mesgar et al. 2024). CR can enhance soil structure by improving porosity and transpiration, leading to better moisture retention. However, the lack of additional air-filled pore spaces, which are beneficial for drainage, may further reduce λ, as air is a poor heat conductor. Additionally, root systems of certain crops may form channels that promote water infiltration and retention, thereby indirectly influencing λ. Consequently, CR can reduce λ by increasing organic matter and improving soil structure.

Soil λ is also a key factor in Nutri $_{av}$, which directly influences agricultural productivity. Soil λ affects soil thermal conditions, moisture conservation, microbial activity, and root development—key contributors to nutrient mobilization. Higher soil λ is typically associated with increased moisture retention, which can enhance Nutri $_{av}$ for plants. However, excessive moisture may lead to nutrient leaching, emphasizing the need for careful irrigation and fertilization management (Chen et al. 2024a; Shah et al. 2024a).

Soil texture significantly influences λ dynamics by altering particle size distribution, porosity, and moisture retention capacity. Different soil textures—sandy, silty, and clay—have distinct TCs. Sandy soils increase λ with moisture content, while clay soils exhibit stable λ when saturated. The increase in moisture improves heat conduction in soils, with clay soils typically being more thermally stable than sandy soils. Loamy soils, composed of sand, silt, and clay, offer balanced λ, making them ideal for agricultural applications (Malek et al. 2021). Studies have focused on how different soil textures impact λ, particularly in relation to moisture content and salinity. Understanding these effects allows farmers and agronomists to optimize SMP by improving thermal efficiency and boosting agricultural yield, especially in response to irrigation, crop management, and climatic fluctuations.

Soil λ is influenced by mineral composition, which plays a significant role in determining its TCs (He et al. 2021; Zou et al. 2019). Zou et al. (2019) emphasized that quartz content, rather than porosity, is the dominant factor in establishing λ models for unsaturated soils with high quartz content. These findings provide engineers with a more efficient approach for predicting soil λ based on various soil properties. The interaction between mineral composition and soil characteristics directly impacts λ, and therefore agricultural productivity (Kolawole et al. 2024; Wu et al. 2025b).

The relationship between soil λ and $T_{soil\ reg}$ is essential for understanding heat transfer in soils. Since λ increases with temperature, particularly in moist soils, factors such as air temperature and seasonal changes must be considered. The $T_{soil\ reg}$ influences critical processes like evaporation and plant transpiration, which are vital for ecosystem stability. Variations in λ, driven by soil composition, highlight the importance of site-specific management strategies to optimize conditions for seed germination and root development. Chen et al. (2024d) pointed out that different λ models exhibit varying levels of accuracy in simulating soil temperature and moisture content, underscoring the need for appropriate measurement techniques for agricultural and environmental applications.

Moisture movement and retention are closely linked to soil λ. As μ increases, λ typically rises, enhancing heat transfer within the soil profile. Water, having a higher λ than air, improves the soil's ability to conduct heat. Soils with higher moisture levels tend to exhibit greater λ because water facilitates more efficient heat conduction than air. Understanding these dynamics is essential for optimizing IP and crop selection based on specific soil moisture conditions (Fu et al. 2024a; Wang et al. 2023a, 2024b). Fu et al. (2024a) highlighted the strong correlation between soil λ and water retention, emphasizing that moisture content significantly influences λ. Their findings suggest that critical moisture levels are closely related to soil hydraulic properties, which may vary with climate, indicating the need for further research on how moisture movement and retention affect λ in diverse environmental conditions.

Soil λ has a significant impact on soil structure and health. The arrangement of soil particles and pores determines λ, affecting moisture retention and temperature regulation. Key factors such as *pb*, soil composition, and aggregation also play major roles in determining λ values. Improving soil structure may optimize TCs, supporting soil health and plant growth (Cai et al. 2019; Shah et al. 2024a; Wu et al. 2025b; Zou et al. 2019). Wu et al. (2025b) conducted a comprehensive analysis of experimental and modelling studies on soil λ, exploring how internal and external factors—such as μ and dry *pb* —affect λ. Their study critiques traditional theoretical and experimental models to predict λ, noting their limitations in capturing soil diversity and emphasizing the increasing role of machine learning in developing more accurate predictive models. Practical applications entail utilizing soil sensors (which include fiber-optic sensors, thermal probes, and IoT-enabled devices) to gather real-time data on soil μ, temperature, and texture. These sensors give ongoing observation of λ dynamics, which can be input into machine learning algorithms to produce predicted maps of soil thermal behaviour. Precise agriculture systems may use these forecasts to improve irrigation scheduling, ensuring water is provided when λ values indicate sufficient heat transfer, thus stabilising root-zone temperatures and improving crop resilience (Pal et al. 2024). Furthermore, remote sensing technology combined with machine learning can provide spatial λ evaluations over large areas, informing focused tillage or mulching strategies. Similarly, Shah et al. (2024a) found that soil microorganisms influence λ, playing a vital role in soil structure and health. Enhanced λ can improve heat transfer mechanisms, potentially impacting soil aggregation and overall soil quality.

4.2 Climate adaptation strategies (CAS) impact on soil thermal conductivity

The CAS have significance for affecting λ, although their effects are complex and depend on the setting. Table 2 summarises the CAS and their influence on λ. Soil mulching (SM), commonly used with CAS, modulates λ by modifying the heat exchange between soil and atmosphere. Straw-organic mulches reduce λ by providing insulating layers that decrease temperature fluctuations and maintain moisture stability. Visconti et al. (2024) found that straw mulches effectively reduce soil λ by recording air within the stalks. The low heat capacity and λ of air contribute to a reduction in heat transfer to the atmosphere, which is beneficial for root growth and soil health, indicating a reduction in soil λ. Conversely, plastic films-inorganic mulches can increase λ in cooler places by holding heat but might accelerate soil warming in warmer areas (Dai et al. 2024; Zhao et al. 2023). However, the impacts of SM on soil biota leading to organic matter decomposition and λ across diverse climatic conditions are little investigated. For example, while plastic mulches promote λ predictability in managed

Table 2 Summary of climate Adaptation Strategies (CAS) and their influence on thermal conductivity (λ)

Climate adaptation strategies (CAS) ID	Impact on λ	Examples / Mechanism
Soil mulching	Modulates temperature fluctuations, impacts λ	Organic mulches (straw) reduce λ through insulates soil by trapping air (poor conductor) and stabilizing moisture. While, inorganic mulches (plastic) increase λ, by traps temperature, reduces air-filled pores, and increases soil temperature
Climate change	Affects moisture dynamics, influences λ by changes in temperature, moisture patterns, and extreme weather events	Dry conditions, and heavy rainfall
Precision agriculture	Enhances soil monitoring and management, optimizing λ through data driven practices	Uses real-time data to balance irrigation and soil moisture by using soil sensors, machine learning applications

environments, their longevity in ecosystems of soil raises apprehensions regarding microplastic pollution and modified hydraulic properties (Bai et al. 2024; Khalid et al. 2023; Song et al. 2025; Thrän et al. 2024). We confirm the climate-dependency of mulch effects, noting that plastic mulches are beneficial for early-season warming in temperate zones but risky in the tropics.

As climate change progresses, soil λ's impact on heat flow density, precipitation patterns, and soil temperature dynamics becomes increasingly significant (Jérémy et al. 2025). Variations in λ can influence local and regional climate conditions, affecting surface energy balance and precipitation simulations (Nazim et al. 2025; Zaqout and Andradóttir 2024). Understanding these interactions is essential for developing adaptive agricultural practices that respond to shifting climatic patterns.

Recent developments in sensor networks and machine learning-driven analytics have transformative promise for CAS. Soil λ produced by ML models may direct the choice of mulching materials as organic versus inorganic, based on current climate data and soil μ patterns. Embedded sensors in agricultural fields can identify early indicators of temperature extremes, activating automatic changes in irrigation or residue management to alleviate λ variations (Huang et al. 2024).

4.3 Integrated effects of SMP and CAS across soil types and climates for optimizing λ

Soil thermal conductivity (λ) plays a vital role in agricultural productivity and ecosystem resilience, necessitating the integrated application of SMP and CAS tailored to specific soil types and climatic conditions, as outlined in Table 3. The interaction between SMP, CAS, and soil λ is multifaceted, involving variables such as soil texture, structure, moisture content, and organic matter composition (Wu et al. 2025b).

Different soil types exhibit distinct λ behaviours. For instance, sandy soils, which experience high λ variability due to rapid moisture fluctuations, benefit significantly from organic matter enrichment and conservation tillage. When paired with organic mulching and precision irrigation (CAS), these practices help stabilize moisture levels and buffer temperature extremes. Organic matter enhances soil porosity and water-holding capacity—both crucial for regulating heat transfer within the soil profile (Gutema et al. 2023).

In contrast, clayey soils, characterized by fine-textured, water-retentive pores and typically higher λ, require reduced tillage and specific soil amendments to avoid compaction and waterlogging. These SMP interventions, when combined with inorganic mulching (CAS), can regulate moisture and support adequate heat transfer without compromising soil structure.

Loamy soils, with their balanced texture and moderate λ, are particularly responsive to crop rotation strategies (SMP) enhanced by mixed mulching systems or agroforestry practices (CAS), which provide seasonal thermal regulation and support overall soil health.

Climate-specific strategies further optimize these approaches. In arid regions, drip irrigation and reflective mulches reduce spikes in λ caused

Table 3 Integration of soil management practices (SMP) and climate adaption strategies (CAS) on soil thermal conductivity (λ) across various soil types and climatic conditions

Soil type/climate		Key SMP-CAS interactions	Knowledge gaps for future study
Sandy soils	Arid/Temperate	Organic matter + precision irrigation stabilizes λ Mulching reduces evaporation-induced λ rises	Long-term study of impacts of biochar versus compost on λ in arid sandy soils. Furthermore, optimum irrigation of parameters for λ stability
Clayey soils	Humid/cold	Reduced tillage practices + inorganic mulches balances λ values of soil Gypsum amendments improve soil structure without λ loss	Future Research on trade-offs between drainage CAS and SOM preservation Impact of freeze–thaw cycles on amended clay λ
Loamy Soils	All climates	Cover crops + agroforestry sustain modest λ Mixed mulching adjusts to seasonal λ variations	Climate-specific thresholds for mulch composition (organic to inorganic ratios)
Organic matter (OM) of soil	Tropical/Temperate	High-lignin residues slow λ variability in tropics Biochar enhances λ stability in temperate zones	Decomposition rates of novel amendments such as biochar on λ. The OM with λ relationships under extreme rainfall variability need more investigation
Precision agriculture	Arid/humid	Sensor-driven irrigation improves λ in real-time Machine learning predicts λ using soil-climate data	Further research should be undertaken to λ models across soil-climate gradients, as well as the cost-effectiveness of IoT systems for real-time λ measurements
Soil mulching	Extreme climates	Reflective mulches in arid regions decrease λ values Mulches in cold climates preserve soil temperature	Sustainable mulch options for soil λ control as well as microplastic impacts on λ in long-term mulch use

by excessive evaporation. In humid climates, raised beds and organic mulches help mitigate water saturation and maintain balanced thermal regimes. In cold climates, no-till farming and dark-colored mulches are effective in conserving heat during freeze–thaw cycles.

Innovative solutions such as biochar applications and smart irrigation technologies, supported by policies promoting climate-smart agriculture, present promising avenues for expanding these integrated strategies. However, critical knowledge gaps remain regarding the long-term impacts of SMP-CAS combinations, particularly in terms of environmental feedback loops, economic viability, and scalability.

Therefore, a deeper understanding of the integrated effects of soil type, climate, and management practices on λ is essential for designing effective, sustainable strategies that enhance soil thermal properties, improve crop performance, and strengthen resilience against climate variability.

5 Summary of knowledge gaps and future research directions

There is a pressing need for comprehensive research on how soil λ influences key agricultural factors such as tillage systems, water retention, and nutrient availability across various soil types. Understanding these interactions is crucial for developing improved agricultural practices that can enhance crop yields and sustainability by optimizing soil management strategies. One area that requires further exploration is the complex relationship between tillage methods and soil λ. It is essential to assess how traditional tillage compares to conservation tillage in influencing water retention and λ under different environmental conditions. Optimizing tillage systems to enhance soil health, improve water conservation, and boost agricultural productivity, particularly in the face of climate change, would benefit from the integration of soil sensors and remote sensing technologies. These tools would enable the collection of detailed λ and moisture retention data, followed by statistical analysis to uncover patterns and correlations.

Additionally, investigating the dynamic relationship between soil λ and soil temperature could improve predictive models for crop growth and microbial activity. Incorporating external factors, such as mulching and cover cropping, into these models would enhance agricultural planning and sustainability. Understanding how different soil textures affect water retention and λ is another critical research direction. This includes exploring the potential benefits of integrating λ measurements with precision agriculture technologies to optimize irrigation strategies and improve crop yields. Focusing on how these TCs influence irrigation practices will help refine approaches to water management in agriculture.

Another knowledge gap exists in understanding the mechanisms through which λ affects nutrient solubility and availability. This area of research is fundamental for improving soil management and fertility practices, which are crucial for long-term agricultural success. Furthermore, studies should examine the impacts of climate change on λ fluctuations and their subsequent effects on soil temperature dynamics and nutrient cycling. Such research would be pivotal for developing adaptive agricultural strategies that are resilient to changing environmental conditions.

Research on the relationship between OM and soil λ could provide valuable insights into improving soil health. By analyzing how varying OM levels affect heat transfer and water dynamics, scientists can develop better soil conservation methods that optimize these TCs. Moreover, the integration of λ into precision agriculture practices is an area that warrants further study. Investigating how soil TCs can guide irrigation and nutrient management decisions will contribute to more efficient agricultural practices.

The influence of mineral content on λ and its effect on overall soil health and productivity is another crucial aspect of future research. Machine learning techniques could be employed to improve the predictive accuracy of λ models based on the mineral composition of different soils. Additionally, more research is needed to assess how various irrigation methods—such as surface, drip, and sprinkler irrigation—affect soil λ across diverse soil types. A deeper understanding of how irrigation methods, combined with factors like soil texture, water retention, and compaction, impact λ dynamics will help improve water use efficiency and increase crop productivity.

Another important area for further exploration is how crop rotations influence soil λ. The changes in OM, soil structure, and moisture retention resulting from different crop rotation practices are critical for understanding their long-term impact on soil TCs. Special attention should be given to the seasonal effects of crop rotation, particularly how variations in cover crops and fallow periods influence λ over the course of a year. Additionally, further studies should be conducted on the effects of different mulching materials, both organic and inorganic, on soil λ across various climates and soil types. Investigating the long-term impacts of mulching, especially in combination with other soil management practices like tillage and crop rotation, could reveal valuable information about how these interactions affect soil structure and λ over multiple growing seasons.

6 Conclusions

This research underscores the critical role of soil λ in agricultural systems and highlights the substantial impact that SMP have on soil λ. Understanding the dynamics of λ is essential for enhancing agricultural productivity, improving soil health, and mitigating the effects of climate change. The findings indicate that various SMP, including tillage methods, organic matter management, irrigation practices, and crop rotation, have a direct influence on soil λ. Notably, no-till farming and increased organic matter were found to improve λ, thereby enhancing soil water retention and stabilizing temperature. The interaction between λ and environmental factors becomes increasingly significant in determining soil health and productivity.

As climate conditions continue to evolve, it is essential to adopt SMP and CAS to preserve soil health and ensure sustainable agricultural practices. Different soil textures—such as sandy, silty, and clayey soils—exhibit unique TCs that affect λ. Understanding these differences is vital for developing targeted irrigation and crop management strategies tailored to specific soil types.

Additionally, identifying existing knowledge gaps in areas such as irrigation techniques, crop rotation, and soil mulching is crucial for deepening our understanding of λ dynamics. Future research should prioritize these areas, particularly focusing on the long-term effects and interactions of various agricultural practices. By addressing these knowledge gaps, we can develop more effective strategies for managing soil thermal conductivity, ultimately promoting more sustainable and productive farming systems.

Author's contribution Conceptualization: A.G.A, L.S.A, A.C.-C., and J.F-G. Methodology: A.G.A, L.S.A, A.C.-C., and J.F-G. Software: A.G.A and L.S.A. Validation: A.C-C. and J.F-G. Formal analysis: A.G.A. and L.S.A. Investigation: A.G.A. and L.S.A. Data curation: A.C.-C. and J.F-G. Writing-original draft preparation: A.G.A. and L.S.A. Writing-review and editing: A.C.-C. and J-F-G. Supervision: A.C.-C. Project administration: A.G.A. and L.S.A. Funding acquisition: A.G.A. and L.S.A.

Funding Funding for open access publishing: Universidad de Granada/CBUA. Funding for open access charge: Universidad de Granada / CBUA.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

References

Abu El-Magd SA, Masoud AM, Hassan HS, Nguyen N-M, Pham QB, Haneklaus NH, Hlawitschka MW, Maged A (2024) Towards understanding climate change: impact of land use indices and drainage on land surface temperature for valley drainage and non-drainage areas. J Environ Manage 350:119636

Abu-Hamdeh N, Reeder R (2000) Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. Soil Sci Soc Am J 64:1285–1290

Allende-Montalbán R, San-Juan-Heras R, Martín-Lammerding D, Delgado MDM, Albarrán MDM, Gabriel JL (2024) The soil sample conservation method and its potential impact on ammonium, nitrate and total mineral nitrogen measurements. Geoderma 448:116963

Al-Shammary A, Kouzani A, Gyasi-Agyei Y, Gates W, Rodrigo-Comino J (2020a) Effects of solarisation on soil thermal-physical properties under different soil treatments: a review. Geoderma 363:114137

Al-Shammary AAG, Kouzani A, Gyasi-Agyei Y, Rodrigo-Comino J (2020b) A comparison of different solarisation systems and their impacts on soil thermal characteristics—an application in cultivated soils close to Baghdad, a highly populated city in Iraq. Environ Monit Assess 192:1–13

Al-Shammary AAG, Caballero-Calvo A, Jebur HA, Khalbas MI, Fernández-Gálvez J (2022) A novel heat-pulse probe for measuring soil thermal conductivity: field test under different tillage practices. Comput Electron Agric 202:107414

Al-Shammary AAG, Lahmod NR, Fernández-Gálvez J, Caballero-Calvo A (2023) Effect of tillage systems combined with plastic film mulches and fertilizers on soil physical properties in a wheat-agricultural site in southern Iraq. Cuadernos De Investigación Geográfica 49(2):51–63

Al-Shammary AAG, Caballero-Calvo A, Fernández-Gálvez J (2024) Evaluating the performance of a novel digital slippage system for tractor wheels across varied tillage methods and soil textures. Agriculture 14(11):1957

Bai J, Chen D, Zhang Z, Huang Y, Bai Y, Hao J, Song J, Li N, Ren G, Wang X, Yang G, Yadav S, Feng Y, Wang X (2024) Minimizing environment footprint through half-plastic film mulch and straw incorporation in maize-based system. Agr Ecosyst Environ 367:108957

Ball KR, Guo Y, Hallett PD, Smith P, Moreno-Ramón H, Morris NL, Malik AA (2025) Soil organic and inorganic carbon interactions under tillage and cover cropping determine potential for carbon accumulation in temperate, calcareous soils. Soil Tillage Res 247:106369

Bayat H, Ebrahimzadeh G, Mohanty BP (2021) Investigating the capability of estimating soil thermal conductivity using topographical attributes for the Southern Great Plains, USA. Soil Tillage Res 206:104811

Cai S, Zhang B, Cui T, Guo H, Huxford J (2019) Mesoscopic study of the effective thermal conductivity of dry and moist soil. Int J Refrig 98:171–181

Cárceles Rodríguez B, Durán-Zuazo VH, Soriano Rodríguez M, García-Tejero IF, Gálvez Ruiz B, Cuadros Tavira S (2022) Conservation agriculture as a sustainable system for soil health: a review. Soil Syst 6(4):87

Cerecetto V, Leoni C, Jurburg SD, Kampouris ID, Smalla K, Babin D (2024) Pasture-crop rotations modulate the soil and rhizosphere microbiota and preserve soil structure supporting oat cultivation in the Pampa biome. Soil Biol Biochem 195:109451

Chen ZX, Guo XX, Shao LT, Li SQ (2020) On determination method of thermal conductivity of soil solid material. Soils Found 60(1):218–228

Chen C, Pei J, Li B, Fang C, Nie M, Li J (2024a) Nutrient addition enhances the temperature sensitivity of soil carbon decomposition across forest ecosystems. Glob Change Biol 30(10):e17543

Chen P, Ruan F, Li S, Qin D, Xu S (2024b) Exploring crop root-soil heat relationships to optimally predict soil temperatures in greenhouse spaces. Plant Soil 505(1):595–613

Chen T, Fei W, Narsilio GA (2024c) Effective thermal conductivity of granular soils: a review of influencing factors and prediction models towards an investigation framework through multiscale characters. Can Geotech J. https://doi.org/10.1139/cgj-2023-0465

Chen X, Zhao Y, Cheng J, Hu Y, Si B, Li M, Siddique KHM, Azad N, He H (2024d) Extended HYDRUS-1D freezing module emphasizes thermal conductivity schemes for simulation of soil hydrothermal dynamics. Geoderma 448:116946

Cheng L, Zhang Y, Zhang A, Sun Y, Cao Y, Xu Z (2024) Investigation of measurement methods for soil thermal conductivity based on optical frequency domain reflection technology. Int J Therm Sci 198:108889

Chu X, Flerchinger GN, Ma L, Fang Q, Malone RW, Yu Q, He J, Wang N, Feng H, Zou Y (2022) Development of RZ-SHAW for simulating plastic mulch effects on soil water, soil temperature, and surface energy balance in a maize field. Agric Water Manag 269:107666

Dai Y, Zhang P, Chao J, Liu G, Guo L, Senge M (2024) Effects of inorganic mulching on soil hydrothermal environment and tomato characters in the presence of unheated greenhouse cultivation. Sci Rep 14(1):4337

Ding Y, Mu C, Wu T, Hu G, Zou D, Wang D, Li W, Wu X (2021) Increasing cryospheric hazards in a warming climate. Earth Sci Rev 213:103500

Doneva K, Kercheva M, Dimitrov E, Velizarova E, Glushkova M (2022) Thermal properties of Cambisols in mountain regions under different vegetation covers. Soil Water Res 17(2):113

Ernest B, Yanda PZ, Hansson A, Fridahl M (2024) Long-term effects of adding biochar to soils on organic matter content, persistent carbon storage, and moisture content in Karagwe, Tanzania. Sci Rep 14(1):30565

Esmaeilian Y, Babaeian M, Caballero-Calvo A (2023) Optimization of castor bean (Ricinus communis L.) cultivation methods using biostimulants in an arid climate. Euro-Mediterr J Environ Integr 8(4):823–834

Formigari RC, Tsuha CDHC (2025) Experimental investigation on the impact of the asymmetrical heat exchange and operation modes on the thermal performance of a bored energy pile in unsaturated soil: A case study in Brazil. Geothermics 125:103201

Fu Y, Liu L, Lu Y, Horton R, Ren T, Heitman J (2023b) Estimating soil water retention curves from thermal conductivity measurements: a percolation-based effective-medium approximation. J Hydrol 624:129898

Fu Y, Ghanbarian B, Horton R, Heitman J (2024a) New insights into the correlation between soil thermal conductivity and water retention in unsaturated soils. Vadose Zone J 23(1):e20297

Fu Y, Horton R, Heitman J (2024b) Estimating soil water retention curves over the entire saturation range: a thermal conductivity-based approach. J Hydrol 645:132138

Guo L, Guo H, Wang B, Zhang M, Peng Y, Zhao J, Li A, Xie J (2024) Numerical investigation of MICP to improve soil thermal conductivity. KSCE J Civ Eng 29:100121

Gutema T, Kebede E, Legesse H, Fite T (2023) Integrating multiple soil management practices: a system-wide approach for restoring degraded soil and improving Brachiaria productivity. Agrosyst, Geosci Environ 6:e20360

Haque MA, Ku S, Haruna SI (2024) Soil thermal properties: influence of no-till cover crops. Can J Soil Sci 104(3):246–256

Haruna SI, Anderson SH, Nkongolo NV, Reinbott T, Zaibon S (2017) Soil thermal properties influenced by perennial biofuel and cover crop management. Soil Sci Soc Am J 81(5):1147–1156

Haruna SI, Ward ZA, Cartwright AL, Wunner AA, Jackson CA, Berry CR (2023) No-till cover crop effects on the thermal properties of a Paleudult. Soil Tillage Res 231:105717

He H, He D, Jin J, Smits KM, Dyck M, Wu Q, Si B, Lv J (2020) Room for improvement: a review and evaluation of 24 soil thermal conductivity parameterization schemes commonly used in land-surface, hydrological, and soil-vegetation-atmosphere transfer models. Earth Sci Rev 211:103419

He R, Jia N, Jin H, Wang H, Li X (2021) Experimental study on thermal conductivity of organic-rich soils under thawed and frozen states. Geofluids 2021(1):7566669

He R, Jin H, Jia N, Wang H, Jin X, Li X (2022) Thermal conductivity contrast effect of organic soils and its environmental implications. Cold Reg Sci Technol 196:103485

He S, Zhang C, Meng F-R, Bourque CPA, Huang Z, Li X, Han Y, Feng S, Miao L, Liu C (2024) Vegetation-cover control of between-site soil temperature evolution in a sandy desertland. Sci Total Environ 908:168372

Hu J, Nan Z, Ji H (2022) Spatiotemporal characteristics of NPP changes in frozen ground areas of the three-river headwaters region, China: a regional modeling perspective. Front Earth Sci. https://doi.org/10.3389/feart.2022.838558

Huang X, Zhao Y, Guo T, Mao X (2024) Enhancing SWAP simulation accuracy via assimilation of leaf area index and soil moisture under different irrigation, film mulching and maize varieties conditions. Comput Electron Agric 218:108625

Iacuzzi N, Tortorici N, Ida DM, Alaimo F, Cozzolino E, Sarno M, Mori M, Tuttolomondo T (2024) Biodegradable mulching films affect soil temperature and agronomic performance of open field eggplant in hot-arid environments. Ital J Agron 19(4):100025

Ihekweme GO, Shondo JN, Orisekeh KI, Kalu-Uka GM, Nwuzor IC, Onwualu AP (2020) Characterization of certain Nigerian clay minerals for water purification and other industrial applications. Heliyon 6(4):e03783

Jarrah M, Mayel S, Franko U, Kuka K (2022) Effects of agricultural management practices on the temporal variability

of soil temperature under different crop rotations in bad Lauchstaedt-Germany. Agronomy 12(5):1199
Jérémy G, Alexandre P, Peter B, François L (2025) Impact of land cover and climate change on Aquifer Thermal and Energy Storage (ATES) system performance. Geothermics 127:103262
Kang W, Zhang Y, Zhao W, Wu S (2024) The effect of gravel mulch on soil evaporation and resistance: experimental findings and modeling. J Soil Sci Plant Nutr 25:1135
Kashyap B, Kumar R (2021) Sensing methodologies in agriculture for soil moisture and nutrient monitoring. IEEE Access 9:14095–14121
Khaledi S, Delbari M, Galavi H, Bagheri H, Chari MM (2023) Effects of biochar particle size, biochar application rate, and moisture content on thermal properties of an unsaturated sandy loam soil. Soil Tillage Res 226:105579
Khalid N, Aqeel M, Noman A, Fatima Rizvi Z (2023) Impact of plastic mulching as a major source of microplastics in agroecosystems. J Hazard Mater 445:130455
Khan MI, Hwang HY, Kim GW, Kim PJ, Das S (2018) Microbial responses to temperature sensitivity of soil respiration in a dry fallow cover cropping and submerged rice mono-cropping system. Appl Soil Ecol 128:98–108
Klamerus-Iwan A, Ruiz LC, Gómez CM, Warczyk A, Singh PD, Khan MO, Caballero-Calvo A (2024) Assessing water storage capacity and wettability of plants and woody fragments in post-fire environments: a case study in Los Guájares, SE Spain. Trees for People 17:100607
Kňažková M, Hrbáček F (2024) Interannual variability of soil thermal conductivity and moisture on the Abernethy Flats (James Ross Island) during thawing seasons 2015–2023. CATENA 234:107640
Kolawole O, Rehmatullah S, Shah V (2024) Evaluating soil thermal conductivity for buried infrastructure: impact of water salinity, mineral composition, and moisture content on heat transfer. Prog Eng Sci 1(2):100014
Lei H, Bo Y, Wang L, Zhang W (2023) Generalized model for predicting the thermal conductivity of fine-grained soils. Geothermics 113:102752
Li K-Q, Li D-Q, Chen D-H, Gu S-X, Liu Y (2021) A generalized model for effective thermal conductivity of soils considering porosity and mineral composition. Acta Geotech 16:3455–3466
Li C, Luo X, Li Y, Wang N, Zhang T, Dong QG, Feng H, Zhang W, Siddique KHM (2023) Ridge planting with transparent plastic mulching improves maize productivity by regulating the distribution and utilization of soil water, heat, and canopy radiation in arid irrigation area. Agric Water Manag 280:108230
Li Z, Liu H, Wang T, Gong P, Li P, Li L, Bai Z (2024) Deep vertical rotary tillage depths improved soil conditions and cotton yield for saline farmland in South Xinjiang. Eur J Agron 156:127166
Liebhard G, Klik A, Neugschwandtner RW, Nolz R (2022) Effects of tillage systems on soil water distribution, crop development, and evaporation and transpiration rates of soybean. Agric Water Manag 269:107719
Liu W, Li R, Wu T, Shi X, Zhao L, Wu X, Hu G, Yao J, Xiao Y, Ma J, Jiao Y, Wang S (2023) Simulation of soil thermal conductivity based on different schemes: an empirical comparison of 13 models. Int J Therm Sci 190:108301
Liu L, Lu Y, Horton R, Ren T (2024a) Determination of soil water retention curves from thermal conductivity curves, texture, bulk density, and field capacity. Soil Tillage Res 237:105957
Liu X, Chen B, Garg A, Song X, Satyam N (2024b) Review and measurement of thermal properties of soil amended with different biochar types considering unsaturated soil perspective. Indian Geotech J. https://doi.org/10.1007/s40098-024-01063-9
Lozano-Parra J, Maldonado-Clavelle CF, Caballero-Calvo A, Pulido-Fernández M, Gyasi-Agyei Y, Rodrigo-Comino J (2023) Estimation of soil mobilization rates by a rainy period and intense tillage practices in vineyards—a case study in the Maule region (Chile). Hydrol Process 37(4):e14829. https://doi.org/10.1002/hyp.14829
Lunt PH, Fuller K, Fox M, Goodhew S, Murphy TR (2023) Comparing the thermal conductivity of three artificial soils under differing moisture and density conditions for use in green infrastructure. Soil Use Manag 39(1):260–269
Malek K, Malek K, Khanmohammadi F (2021) Response of soil thermal conductivity to various soil properties. Int Commun Heat Mass Transfer 127:105516
Mari JA, Soothar RK, Thidar M, Mangrio MA, Mirjat MU, Katohar I (2024) Effect of plastic film mulch and irrigation water regimes on soil temperature pattern, plant growth and water productivity of maize. Ecol Front 44(4):752–759
Mendis SS, Udawatta R, Anderson SH, Ansari J, Salceda M (2022) Effects of cover crops on soil thermal properties of a corn cropping system. Soil Sci Soc Am J 86(5):1194–1205
Mesgar M, Voroney RP, Lo A, Ardakani OH, Gillespie AW (2024) Chemical composition and thermal stability of topsoil organic carbon: Influence of cropping system and tillage practices. Eur J Soil Sci 75(1):e13459
Mirghafari R, Helforoosh AH, Nikooee E, Habibagahi G, Raoof A, van Genuchten MT (2024) Pore unit cell network modeling of the thermal conductivity dynamics in unsaturated sandy soils: unveiling the role of spanning-wetting phase cluster. Vadose Zone J 23(4):e20350
Muhudin AA, Zami MS, Budaiwi IM, Abd El Fattah A (2024) Experimental study of thermal conductivity in soil stabilization for sustainable construction applications. Sustainability 16(3):946
Najafian Jazi F, Ghasemi-Fare O, Rockaway TD (2024) Natural convection effect on heat transfer in saturated soils under the influence of confined and unconfined subsurface flow. Appl Therm Eng 237:121805
Nazim M, Ghafoor A, Hussain A, Tabassum M, Nawaz A, Ahmad M, Muhammad M, Ali M (2025) Biochar as a climate-smart agricultural practice: reducing greenhouse gas emissions and promoting sustainable farming. Phyton-Int J Exp Bot 94(1):65–99
Pal A, Dubey SK, Goel S, Kalita PK (2024) Portable sensors in precision agriculture: assessing advances and challenges in soil nutrient determination. TrAC Trends Anal Chem 180:117981
Pan Y, Li X, Li S (2024) Effects of different soil thermal conductivity schemes on the simulation of permafrost on the Tibetan Plateau. Geoderma 442:116789

Parajuli SP, Biggs T, de Sales F, Zavala Perez MA, He C, Jones C, Thompson C, Galvez NL, Ciborowski H, Quintino T, Di Napoli C, Montazar A, Yazdi TH, Soucier M (2024) Impact of irrigation on farmworkers' heat stress in California differs by season and during the day and night. Commun Earth Environ 5(1):787

Paramesha V, Kumar P, Francaviglia R, Jyoti Nath A, Mishra G, Mohan Kumar R, Toraskar S, Rakhunde S (2025) Evaluating land use and climate change effects on soil organic carbon. A simulation study in coconut and pineapple systems in west coast India. CATENA 248:108587

Parlak M, Everest T, Tunçay T, Caballero-Calvo A, Rodrigo-Comino J (2022) Soil losses due to leek and groundnut root crop harvesting: an unstudied regional problem in Turkey. Land Degrad Dev 33(11):1799–1809. https://doi.org/10.1002/ldr.4262

Pascoal D, Silva N, Adão T, Lopes RD, Peres E, Morais R (2024) A technical survey on practical applications and guidelines for IoT sensors in precision agriculture and viticulture. Sci Rep 14(1):29793

Quan H, Feng H, Zhang T, Wu L, Dong QG, Siddique KHM (2024a) Response of soil water, temperature, and maize productivity to different irrigation practices in an arid region. Soil Tillage Res 237:105962

Roghangar K, Hayley JL (2024) A study of thermal modeling parameters and their impact on modelled permafrost responses to climate warming. Cold Reg Sci Technol 221:104155

Romio LC, Zimmer T, Bremm T, Buligon L, Herdies DL, Roberti DR (2022) Influence of different methods to estimate the soil thermal properties from experimental dataset. Land 11(11):1960

Różański A (2022) Relating thermal conductivity of soil skeleton with soil texture by the concept of "local thermal conductivity fluctuation." J Rock Mech Geotech Eng 14(1):262–271

Saha AK, McMaine JT, Trooien T, Sexton P, Graham C (2024) Impact of no-till, crop rotation, cover crop, and drainage on soil physical and hydraulic properties. Soil Sci Soc Am J 88(2):239–257

Schjønning P (2021) Thermal conductivity of undisturbed soil–Measurements and predictions. Geoderma 402:115188

Sepaskhah AR, Mazaheri-Tehrani M (2024) A sigmoidal model for predicting soil thermal conductivity-water content function in room temperature. Sci Rep 14(1):17272

Shah MV, Tandel P, Mistry S, Singh S, Panchal RK, Upadhye V, Sinha RP (2024a) Development of state of art test setup to measure thermal conductivity of soils infused with treated and un-treated natural microorganisms. Environ Qual Manage 33(4):713–725

Shah MV, Tandel P, Patel A, Chavda A, Singh S, Panchal RK, Upadhye V, Singh VK, Sinha RP (2024b) Influence of microorganisms on thermal conductivity of soils and its potential impact on soil aggregation. Vegetos. https://doi.org/10.1007/s42535-024-01091-z

Song F, Liu M, Zhang Z, Qi Z, Li T, Du S, Li A, Liu J (2024a) No-tillage with straw mulching increased maize yield and nitrogen fertilizer recovery rate in northeast China. Agric Water Manag 292:108687

Song X, Vanapalli SK, Ren J (2024b) Prediction of thermal conductivity of frozen soils from basic soil properties using ensemble learning methods. Geoderma 450:117053

Song Y, Sun J, Cai M, Li J, Bi M, Gao M (2025) Effects of management of plastic and straw mulching management on crop yield and soil salinity in saline-alkaline soils of China: a meta-analysis. Agric Water Manag 308:109309

Srivastava RK, Purohit S, Alam E, Islam MK (2024) Advancements in soil management: optimizing crop production through interdisciplinary approaches. J Agric Food Res 18:101528

Tai B, Wu Q, Jiang G (2024) Effects of complex environment on soil thermal regime alteration under crushed-rock embankment structures in the permafrost region on the Roof of the World. Cold Reg Sci Technol 217:104023

Tan M, Cui N, Jiang S, Xing L, Wen S, Liu Q, Li W, Yan S, Wang Y, Jin H, Wang Z (2025) Effect of practicing water-saving irrigation on greenhouse gas emissions and crop productivity: a global meta-analysis. Agric Water Manag 308:109300

Tarnawski VR, Leong WH, McCombie M, Bovesecchi G (2022) Estimating soil thermal conductivity by weighted average models with soil solids as a continuous medium. Int J Thermophys 43(12):182

Thotakuri G, Chakraborty P, Singh J, Xu S, Kovács P, Iqbal J, Kumar S (2024) X-ray computed tomography – Measured pore characteristics and hydro-physical properties of soil profile as influenced by long-term tillage and rotation systems. CATENA 237:107801

Thrän J, Garcia-Garcia G, Parra-López C, Ufarte A, García-García C, Parra S, Sayadi-Gmada S (2024) Environmental and economic assessment of biodegradable and compostable alternatives for plastic materials in greenhouses. Waste Manage 175:92–100

Tian Z, Zhang M, Chen J, Knappenberger T (2025) Effects of drying-induced shrinkage on thermal and hydraulic properties of clayey soils. Soil Tillage Res 248:106415

Tschanz P, Walter A, Keller T, Albrecht M (2024) A review of soil tillage impacts on ground-nesting wild bees – mechanisms, implications, and future research perspectives. Agr Ecosyst Environ 375:109224

Usowicz B, Lipiec J (2020) The effect of exogenous organic matter on the thermal properties of tilled soils in Poland and the Czech Republic. J Soils Sediments 20(1):365–379

Venegas HM, Almaraz GMD, Gomez-Ortiz NM, Montes-de-Oca LM, Servín-Campuzano H, González-Avilés M, Alvarado-Gil JJ, Martínez-Torres P (2025) The effect of mineral composition and porosity on the thermal conductivity of clay induced by firing processes at different temperatures and holding times. Mater Chem Phys 333:130325

Visconti F, Peiró E, Pesce S, Balugani E, Baixauli C, de Paz JM (2024) Straw mulching increases soil health in the inter-row of citrus orchards from Mediterranean flat lands. Eur J Agron 155:127115

Vu QH, Pereira J-M, Tang AM (2023) Effect of clay content on the thermal conductivity of unfrozen and frozen sandy soils. Int J Heat Mass Transf 206:123923

Wang Z, Zhang J, Li Q, Zhang N, Feng W (2022b) A theoretical thermal conductivity model for soils treated with microbially induced calcite precipitation (MICP). Int J Heat Mass Transf 183:122091

Wang H, Li D, Xia M, Li X (2023a) Study on thermal conductivity of improved soil under different freezing temperatures. PLoS ONE 18(10):e0292560

Wang Y, Xiao J, Ma Y, Ding J, Chen X, Ding Z, Luo Y (2023b) Persistent and enhanced carbon sequestration capacity of alpine grasslands on Earth's Third Pole. Sci Adv 9(20):eade6875

Wang Y, Zhang Z, Guo Z, Chen Y, Yang J, Peng X (2023c) In-situ measuring and predicting dynamics of soil bulk density in a non-rigid soil as affected by tillage practices: effects of soil subsidence and shrinkage. Soil Tillage Res 234:105818

Wang J, Zheng J, Deng J, Yu Y, Zhu J, Huang X (2024a) Effect of moisture content, temperature, and microstructure on the thermal conductivity of loess and its prediction model. Bull Eng Geol Env 83(5):206

Wang P, Firat ME, Lin Y, Wang T (2024b) Predicting soil thermal properties in freeze-thaw cycles using EFAttNet: a comparative analysis. PLoS ONE 19(7):e0305529

Wang X, Gao Y, Hou J, Yang J, Smits K, He H (2024c) Machine learning facilitates connections between soil thermal conductivity, soil water content, and soil matric potential. J Hydrol 633:130950

Wen Y, Wu X, Liu J, Zhang J, Song L, Zhu Y, Li W, Wang Z (2023) Effects of drip irrigation timing and water temperature on soil conditions, cotton phenological period, and fiber quality under plastic film mulching. Agric Water Manag 287:108435

Wessolek G, Bohne K, Trinks S (2023) Validation of soil thermal conductivity models. Int J Thermophys. https://doi.org/10.1007/s10765-022-03119-5

Wu Y-F, Wu Y-H, Wang Q, Fan L-W, Yu Z-T, Li X-D, Song X (2025a) Study on the effective thermal conductivity of typical light petroleum hydrocarbons-contaminated soil at low temperatures. Int J Heat Mass Transf 236:126293

Wu Y-H, Wu Y-F, Fan L-W, Yu Z-T, Khodadadi JM (2025b) Thermal conductivity of soil: a review on the vast experimental data and predictive models. Int J Therm Sci 208:109486

Xia H, Lai Y, Mousavi Nezhad M, Ma Q (2025) A pore-scale numerical approach to simulate the thermal conductivity of frozen soil. Comput Geotech 179:106991

Xiuling R, Fujun N, Qihao Y, Guoan Y (2024) Research progress of soil thermal conductivity and its predictive models. Cold Reg Sci Technol 217:104027

Xu W, Cao L, Ge R, Li S, Wei Y, Yang Y, Li G, Zhang F (2024a) Long term impact of electrical resistance heating on soil bacterial community based on a field test. Sci Total Environ 950:175292

Xu Y, Zhang Y, Tao W, Deng M (2024b) Spatiotemporal distribution of soil thermal conductivity in Chinese Loess Plateau. Agriculture 14(12):2190

Yang X, Xiong J, Du T, Ju X, Gan Y, Li S, Xia L, Shen Y, Pacenka S, Steenhuis TS, Siddique KHM, Kang S, Butterbach-Bahl K (2024) Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. Nat Commun 15(1):198

Ye X, Yu Z, Zhang Y, Kang J, Wu S, Yang T, Gao P (2022) Mineral composition impact on the thermal conductivity of granites based on geothermal field experiments in the Songliao and Gonghe Basins. China Minerals 12(2):247

Yin W, Fan Z, Hu F, Fan H, He W, Zhao C, Yu A, Chai Q (2023) No-tillage with straw mulching promotes wheat production via regulating soil drying-wetting status and reducing soil-air temperature variation at arid regions. Eur J Agron 145:126778

Yuan Y, Ma Y, Zuo H, Yang C, Yuan L, Chen J (2021) Modification and comparison of thermal and hydrological parameterization schemes for different underlying surfaces on the Tibetan Plateau in the warm season. J Geophys Res: Atmos 126(22):e2021JD05177

Zaqout T, Andradóttir HÓ (2024) Impacts of climate change on winter flood mechanisms: spatial variability, trends, and bivariate frequency of rain-on-snow and soil frost. J Hydrol 638:131439

Zhang M, Tian Z, Zhu Q, Chen J (2023) In-situ assessment of soil shrinkage and swelling behavior and hydro-thermal regimes with a thermo-time domain reflectometry technique. Soil Tillage Res 227:105617

Zhao Y, Mao X, Li S, Huang X, Che J, Ma C (2023) A review of plastic film mulching on water, heat, nitrogen balance, and crop growth in Farmland in China. Agronomy 13(10):2515

Zhao Y, Xu Z, Mao X, Li S, Qi X, Che J (2024) Influence of film color, mulching ratio and soil–mulch contact degree on heat transfer in Northwest China. Agric for Meteorol 357:110208

Zhu D, Ciais P, Krinner G, Maignan F, Jornet Puig A, Hugelius G (2019) Controls of soil organic matter on soil thermal dynamics in the northern high latitudes. Nat Commun 10(1):3172

Zimmer T, Souza VDA, Romio LC, Buligon L, Veeck GP, Stefanello MB, Roberti DR (2023) Estimation of soil thermal properties using conduction and conduction–convection heat transfer equations in the Brazilian Pampa biome. Agric for Meteorol 338:109517

Zou H, Zhang N, Puppala AJ (2019) Improving a thermal conductivity model of unsaturated soils based on multivariate distribution analysis. Acta Geotech 14:2007–2029