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Vapor Transport in Agricultural Soils from a Heat Transfer Perspective: A Review

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ABSTRACT

Water vapor transport in soil is often an underestimated component of agricultural water balance, tightly coupled with heat transfer. This review synthesizes experimental studies across sandy, clay, loam, and silt soils under arid, temperate, and tropical climates, emphasizing how thermal gradients regulate evaporation, redistribution, and condensation. In arid sands, evaporation through dry soil layers can persist at ~1-1.25 mm/day, up to 3-4 times higher than diffusion-only predictions, sustained by wind and pressure fluctuations. Temperate loams and silts exhibit seasonal evaporation-condensation cycles, where straw and plastic mulches reduce vapor losses by 30-47%. Tropical clays, despite high retention, crack under intense heating, with fissures contributing 40-50% total evaporation, losses ~30% post-rain storage within two weeks. Across climates, heat-pore structure feedbacks drive processes such as nightly condensation (up to 0.2 mm) and frost heave. Novel insights arise from coupled heat-mass transport theory and advances in fiber-optic and isotopic sensing that capture dynamic evaporation fronts. Practically, integrating mulching, biochar (10-11% reduction in loams), and irrigation timing with improved coupled models can conserve 20-50% of soil water. Findings highlight soil thermal control as central to climate-resilient farming and call for expanded tropical field studies and model refinement.

1. INTRODUCTION

Soil evaporation - the movement of water from soil to atmosphere as vapor - is a key part of the farmland water cycle and energy balance [1]. In agriculture, this unproductive moisture loss can limit crop water availability and reduce irrigation efficiency. From a heat transfer perspective, evaporation links soil temperature and moisture dynamics [2], with thermal energy driving phase change and vapor diffusion [3]. Dry periods and arid climates amplify this coupling because of intense heating and low humidity. In contrast, humid or temperate regions usually show moderate effects, except during heat waves or droughts. Soil vapor fluxes depend on soil properties (texture, structure, retention) and climate (heat input, atmospheric demand), requiring a broad review across types and zones.

Since 2020, research on soil vapor transport has expanded, reflecting growing concerns over water scarcity and climate extremes. Studies show rising evaporative demand [4] and increasing droughts in all climate zones [5], leading to dry soil layers (DSL) where vapor dominates transport, complicating evaporation prediction. Coarse soils dry quickly, forming DSLs and vapor-driven flux [6], while fine soils retain water but develop strong thermal gradients and cracks for vapor escape; loams are intermediate. Soil thermal conductivity and heat capacity, both moisture-dependent, influence evaporation. As soils dry, lower conductivity raises surface heating, increasing vapor gradients [7], while wet soils with high heat capacity warm slowly and follow energy-limited evaporation. While individual studies have examined sandy, clayey, loamy, and silty soils across different climates, their findings remain fragmented, often focusing on either laboratory or field scales without cross-comparison. Moreover, many land-surface and hydrological models still treat soil heat and moisture flows separately or with simplified evaporation physics, leading to significant biases in arid and semi-arid regions when vapor transport is neglected. Likewise, practical guidance for farmers remains inconsistent, with limited clarity on how mulching, tillage, or soil amendments perform under contrasting climates.

This review addresses these gaps by systematically synthesizing experimental studies up to recent studies, explicitly comparing soil textures (sand, clay, loam, silt) and climate zones (arid, temperate, tropical). It highlights how thermal gradients drive evaporation, redistribution, and condensation, quantifies key ranges of vapor fluxes, and evaluates management interventions (mulching, biochar, irrigation timing). Importantly, the review bridges soil physics and heat transfer theory with agricultural practice, providing a unique cross-disciplinary perspective. By consolidating recent advances—including fiber-optic sensing and isotopic tracing—this work contributes both to improved coupled heat-moisture modeling and to actionable strategies for climate-resilient water management.

2. THEORY

Coupled Heat and Vapor Transport: Soil vapor transport arises from coupled heat and mass transfer. Philip and de Vries [8] showed that both moisture and temperature gradients drive water movement in unsaturated soils. Modern presentations of the theory (e.g., Saito et al. [9] and Nassar and Horton [10]) often use the following form of the moisture mass balance:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K_{lh}\frac{\partial h}{\partial z} + K_{lT}\frac{\partial T}{\partial z} + K_{vh}\frac{\partial h}{\partial z} + K_{vT}\frac{\partial T}{\partial z} + K_{lh}\right) \tag{1}$$

In a temperature gradient, vapor moves from warm to cool zones (thermal diffusion / Soret effect). Higher soil temperatures increase vapor pressure (Clausius-Clapeyron relation), pushing vapor toward cooler zones where it may condense (Kelvin equation). This drives daily evaporation-condensation cycles: Daytime upward movement to the surface, nighttime cooling, and condensation near the surface or upper layers.

Evaporation Stages and Dry Layer Formation: Evaporation from wet soil follows stages: Stage 1 (constant rate) is liquid-supplied and energy-limited. Stage 2 begins when the evaporation front retreats. At this point, a dry soil layer (DSL) forms, through which vapor diffuses and slows evaporation. Stage 3 is very slow, driven by deep vapor diffusion. DSL thickness controls Stage 2 rates, with very thick layers enabling thermal vapor pumping or pore convection (Figure 1).

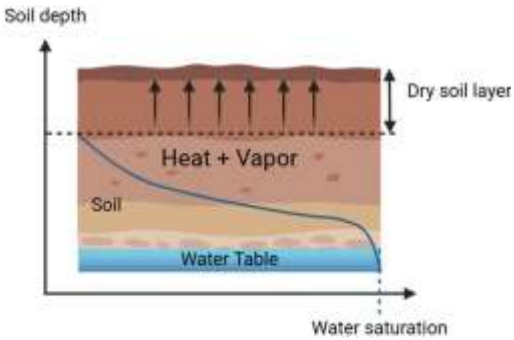

Figure 1. Heat and vapor movement in DSL

Driving Forces: Vapor flow is driven by vapor concentration gradients and temperature gradients that create them. Diffusion generally follows Fick's law, but wind and atmospheric pressure changes can enhance transport, especially in thick DSLs. Solar heating creates strong daytime upward gradients; nighttime cooling can reverse them, leading to daily "breathing" of vapor. Heating/cooling cycles induce internal condensation-evaporation shifts.

Soil Thermal Properties: Thermal conductivity and heat capacity, dependent on moisture and texture, affect heat flow and thus vapor movement. Wet soils conduct heat deeper, driving deeper evaporation; dry soils insulate, intensifying near-surface heating and upward gradients. In some cases, vapor moves downward toward colder zones (e.g., freezing fronts), condensing as ice and contributing to frost heave.

Retention Curve and Temperature: The soil-water retention curve shifts with temperature; warmer soils hold less water at the same matric potential, releasing vapor before bulk drying. Models now incorporate temperature effects to predict vaporization potential.

Soil Texture and Structure: Texture and pore structure control vapor pathways. Sands drain quickly, favoring vapor diffusion; clays retain water longer, but once dry, vapor can dominate. Drying alters structure—especially in clays—causing cracks that increase evaporation by bypassing the DSL and enhancing heat penetration.

Theoretical Summary Predictions: (1) Sands - rapid DSL, dominant vapor diffusion, external enhancement; (2) Clays - delayed vapor release, cracking-driven later-stage evaporation; (3) Loams/Silts - intermediate behavior; (4) Arid climates - extended vapor-driven regimes; (5) Humid/temperate - frequent wetting keeps Stage 1 dominant with short vapor bursts during drying.

3. REVIEW METHODS

Literature Search and Selection: We systematically searched peer-reviewed experimental studies (until 2025) on soil evaporation, moisture transport, and coupled heat-moisture processes using Web of Science, Scopus, and Google Scholar. Keywords included "soil evaporation experiment", "soil vapor transport", "thermal gradient soil moisture", "dry soil layer evaporation", "mulch evaporation experiment", and "soil type evaporation" (sand, clay, loam, silt) under various climates (arid, temperate, tropical). We also screened key journals (e.g., Water Resources Research, Vadose Zone Journal, Agricultural and Forest Meteorology, Soil Science Society Journal, Journal of Hydrology, Agricultural Water Management). Studies were included if they (1) were published until 2025, (2) observed soil evaporation or moisture redistribution with explicit heat effects, and (3) focused on agricultural or near-surface soils.

Review Synthesis: Findings were synthesized within each category to identify consistent patterns and key differences, with comparisons where possible (e.g., evaporation reduction from mulching across climates, sand vs clay under equal heat input). Results are detailed in the "Review Results".

Uncertainty: Many of the included studies rely on laboratory columns or small-scale lysimeters, which may not capture the heterogeneity of field soils. For example, Balugani's column experiments and lysimeter work had sample numbers limited to controlled conditions. For this reason, the review explicitly distinguishes between lab and field findings, often noting that field evaporation rates are 3-4 times higher than lab predictions. Synthesis is done by categorizing soils (sand, clay, loam, silt) and climates (arid, temperate, tropical), allowing comparison across small sample sizes to detect consistent patterns.

4. REVIEW RESULTS

4.1 Sandy soils: Vapor transport under arid conditions

Characteristics: Sandy soils, with coarse texture and large pores, drain quickly and develop dry surface layers early. Once a dry layer forms, vapor diffusion dominates upward water transport. In arid and semi-arid climates, high solar heating and low humidity amplify vapor fluxes in sandy agricultural soils.

Laboratory Column Experiments: Balugani et al. [11] used sand columns with a 50-70 cm DSL under constant and cyclic heating plus airflow to simulate desert conditions (Table 1). Evaporation (~0.3 mm/day) exceeded Fickian diffusion predictions, attributed to barometric pressure fluctuations, which alternately pulled and pushed vapor. Including pressure-driven advective flow in models matched observations. Daily heating-cooling cycles caused “breathing” of the sand column, maintaining upward vapor flux even under very dry conditions.

Field Lysimeter Observations: In semi-arid Spain, Balugani et al. [5] found summer groundwater evaporation of ~1.25 mm/day (2012) and ~1.05 mm/day (2015) with a 70 cm DSL. Rates exceeded lab values by 3-4 times, driven mainly by soil temperature fluctuations rather than diffusion or pressure changes. Models like HYDRUS-1D under-predicted rates, highlighting the need to couple heat and vapor transport.

Wind and Convection: Wind enhances vapor removal during stage 2 by maintaining a strong gradient. In sand, the effect is smaller than in finer soils but still present; high air permeability allows some advective vapor transport. Pressure pumping is particularly relevant in sands, as shown in Balugani’s lab work [11].

Thermal Imaging and Internal Sensors: Guo et al. [12] used fiber-optic sensors to track the evaporation front in sand columns, finding distinct RH and temperature changes at the front. Vapor flux peaked then declined as the front deepened. RH was highest near the front and lowest at the surface, challenging assumptions of uniform vapor distribution.

Summary: Sandy soils in hot, dry climates sustain significant thermally driven vapor transport (1-2 mm/day in extreme cases). Even after surface drying, thermal gradients, permeability, and drivers like wind and pressure changes maintain losses. For agriculture, bare sandy soils require conservation measures to reduce prolonged evaporation.

4.2 Clay soils: Desiccation, cracking, and tropical humid conditions

Characteristics: Clay soils have high water-holding capacity and small pores, delaying vapor-dominated drying but adding complexity. As clays dry, shrinkage forms desiccation cracks, altering exposure and pathways for heat and vapor flow. Common in temperate and tropical agriculture (e.g., paddy fields, vertisols, humid tropical clays), these soils often face strong sun or seasonal droughts, making vapor transport understanding vital for irrigation and soil health.

Evaporation and Cracking: Clay drying shows two-phase evaporation, but cracks during the falling-rate stage can extend Stage 1-like loss (Table 2). Mathers et al. [13] found that cracking reset the drying front deeper. Bin Alam et al. [14] showed that wetter clay dried more slowly but cracked more severely (up to 7 mm wide). These cracks increased total moisture loss by bypassing the dry layer’s resistance. Cracks also allowed deeper heat penetration, accelerating evaporation—models without cracking under-estimate losses.

Tropical Climate Effects: In humid tropics, clays start wet, then bake under the sun; polygonal cracks cause rapid water loss despite high humidity. In India 2021, clay-loam lost ~30% of post-rain water in two dry weeks, with cracks responsible for much of the loss. Earlier work found that cracks can contribute 40-50% of total evaporation. Thermal imaging shows cracks as evaporation hotspots.

Modeling and Special Conditions: Shokri-Kuehni et al. [15] modeled evaporation in cracking clays, showing that neglecting cracks underestimates vapor loss. In frozen clays, vapor transport under thermal gradients can form ice lenses (“pot-cover” effect), with agricultural parallels—mulch could trap vapor and re-condense moisture in hot climates.

Mulching: Plastic mulch on clay-loam [16, 17] reduced evaporation and trapped vapor, with 10-15% re-condensing and returning to the soil, effectively conserving water.

Humid Tropical Clays: High plasticity clays in humid tropics can heat to 50-60°C, creating strong vapor pressure gradients. Cracking accelerates drying even in humid air and causes uneven wetting after rain. Covering the soil reduces direct heating and crack severity.

Thermal Aspects: Evaporative cooling initially lowers surface temperature, but once dry, crack interiors heat rapidly. Drying sharply reduces thermal conductivity, insulating deeper layers until cracks bypass insulation.

Summary: Clay soils’ high retention prolongs stage-1 drying, but cracking triggers a secondary evaporation surge. Management should target reducing direct heating and cracking through mulches, residue cover, or soil amendments.

4.3 Loam and silt loam soils: Intermediate behavior in temperate environments

Characteristics: Loam and silt loam soils balance sand, silt, and clay, giving moderate permeability and water holding capacity. Found in prime agricultural areas worldwide, they show intermediate evaporation—slower than sand but faster than clay. Temperate climate studies often focus on loams under field conditions, though here only bare soil evaporation is considered.

Table 1. Key experimental studies on vapor transport in sandy soils

Citation	Study Type	Main Findings
Balugani et al. [11]	Lab sand columns	Evaporation ≈ 0.3 mm/day, higher than diffusion. Pressure changes caused “breathing”, sustaining vapor flux.
	Wind effect in sand	Wind aids vapor removal; pressure pumping is important.
Balugani et al. [5]	Field lysimeter (Spain)	Evaporation ≈ 1-1.25 mm/day, 3-4× lab rates. Driven by soil temperature, models under-predicted.
Guo et al. [12]	Sand column sensors	Tracked evaporation front. Vapor peaked then declined; RH not uniform.

Table 2. Key studies on clay soil evaporation and cracking

Citation	Main Findings
Mathers et al. [13]	Cracking resets the drying front deeper; it extends Stage-1-like evaporation beyond the normal falling-rate stage.
Bin Alam et al. [14]	Wetter clay dried more slowly but cracked more severely (up to 7 mm width), increasing total moisture loss; cracks bypass the dry layer resistance and enhance heat penetration.
Shokri-Kuehni et al. [15]	Modeled evaporation in cracking clays; neglecting cracks leads to underestimation of vapor loss.
Kader et al. [16] Tang et al. [17]	Plastic mulch on clay-loam reduced evaporation, trapped vapor, and enabled 10-15% re-condensation, conserving soil water.

Table 3. Key Studies on evaporation in loam and silt loam soils

Citation	Main Findings
Iden et al. [18]	Compared silt loam vs. sand under wind, wind + heat, and wind + heat + low humidity. Found silt loam sustained longer in Stage 1 but dropped faster in Stage 2.
Wang et al. [1]	Studied decomposed straw in loam; reduced evaporation by 3-32% over 60 days, improved porosity and aggregation.
Zou et al. [19]	In silt loam, large pores emptied first in Stage 1, and small pores sustained Stage 2. Isotopes confirmed preferential evaporation from larger pores.
Zhang et al. [20]	Field measurements: mulching reduced evaporation—straw by ~30-40%, plastic by 38-47%.
Li and Wang [21] Parlin et al. [22]	Loess soils: salt crusts increased surface temperature but reduced evaporation slightly by blocking vapor flow.

Laboratory Studies - Evaporation Profiles: Iden et al. [18] compared silt loam and sand under wind, wind + heat, and wind + heat + low humidity (Table 3). Silt loam had a longer Stage 1 due to capillarity, but Stage 2 dropped faster. Radiative heating caused strong diurnal swings, with daytime spikes from deeper vapor supply and possible nighttime recondensation. Sand dried faster, showing steady, low evaporation once in Stage 2. Wind mainly affected silt loam's Stage 1; later, soil diffusion limited rates.

Field Measurements: In temperate loams, bare soils can evaporate ~2-3 mm/day after rain, dropping below 0.5 mm after a week of dry. Straw mulch reduced rates by ~30-40% [20], mainly via shading and vapor barrier effects; plastic mulch reduced rates by 38-47%. These effects are consistent across loam soils.

Organic Matter Effects: Wang et al. [1] found decomposed straw in loam reduced cumulative evaporation by 3-32% over 60 days, improving porosity and moisture retention. Later decomposition stages increased "evaporation resistance" by enhancing aggregation and water-holding pores.

Pore-Scale & Isotopes: Zou et al. [19] observed in silt loam that large pores emptied first in Stage 1, small pores sustained Stage 2 vapor flux. Isotopic enrichment near the surface confirmed preferential evaporation from larger pores.

Microclimate and Management: In Poland, no-till loam with residues was cooler and lost ~20% less water early in the season; differences faded as residues decomposed. Controlling soil heat input via tillage or residue helps reduce evaporation during key periods.

Loess (Silt) under Heat: Loess soils, common in China, Europe, and the Americas, dry quickly initially, then sharply slow as a dry layer forms. Salt crusts in loess can raise surface temperatures but modestly reduce evaporation by blocking vapor flow [21, 22].

Summary: Loams sustain higher early evaporation than sands and dry more steadily than clays. Surface management—mulching, cover crops, no-till—effectively reduces heat input and vapor loss. In temperate climates, frequent rain limits thick dry layers, but during drought, loams behave more like arid soils, making infiltration maximization and evaporation reduction key for water productivity.

4.4 Effects of climate: Arid vs. Temperate vs. Tropical comparisons

Arid and Semi-Arid Climates: High evaporation, intense solar radiation, wind, and low humidity cause soils to shift quickly to vapor-dominated drying after surface wetting ends. Thick, persistent DSLs form in sands, loams, and clays (clays may crack). Strong day-night temperature swings drive vapor flux oscillations for months without rain. In semi-arid trials, soil temperatures at 10 cm depth fluctuated by 15-20℃ each day. These fluctuations were tightly linked to evaporation rates. Bare-soil evaporation can initially reach 5-6 mm/day for loam/clay, dropping to 1-2 mm/day (sand/loam) or 0.5-1 mm/day (clay) in stage 2. Seasonal losses can total 100-300 mm. Nighttime condensation can slightly recharge upper layers, and improved models show 20-30% better soil moisture predictions when vapor transport is included.

Temperate Climates: Moderate evaporative demand and frequent wetting-drying cycles limit thick DSL formation. After ~10 dry days, evaporation can fall to ~0.1 mm/day; rains reset drying stages. Vegetation often shades soil, reducing evaporation. Smaller thermal gradients than in arid zones lead to weaker vapor flux, though clear nights can cause dew or shallow condensation, adding up to 0.2 mm overnight. Seasonal bare-soil losses range from 50-150 mm, about half those in arid regions.

Tropical Climates: High temperatures combine variable humidity and seasonal rainfall. Wet seasons are energy-limited; dry seasons resemble subtropical summers. Early dry-season evaporation is slowed by humidity; later, heat and drying accelerate stage 2 losses. Some tropical clays self-mulch, reducing evaporation. Mulching can promote nighttime condensation, increasing upper-layer moisture by 5-10%. Humid tropics have limited bare-soil evaporation; tropical arid zones mirror arid climates. Extreme rains can trigger short-term high evaporation once the soils drain.

Seasonal Cold (Freeze-Thaw): In temperate and tropical high-altitude soils, vapor moves toward freezing fronts, forming ice lenses. Sandy soils can frost-heave solely from vapor-supplied ice growth.

Overall: Arid climates maximize vapor transport; temperate zones see it episodically; tropical climates either limit it (humid) or amplify it (hot/dry). Ignoring vapor flow can mispredict soil moisture persistence. Climate change may shift transitional zones toward higher evaporative losses, making arid-zone practices (e.g., mulching) relevant in cooler regions and inspiring cross-climate water management strategies.

5. DISCUSSION

The findings in this review show the close link between heat transfer and water vapor movement in soils, with key agricultural implications:

(1) Vapor Transport in Dry Soils: Significant vapor flux persists even in dry soils, sometimes exceeding 1 mm/day in arid sands [5] and contributing up to 20% of seasonal evapotranspiration. This indicates that irrigation strategies and water-saving interventions must account for vapor-driven losses even after surface drying, making mulches, surface coverings, and crop residues indispensable for sustainable water use in dryland farming.

(2) Coupled Heat and Mass Flow: Soil temperature gradients are a dominant driver of vapor movement. For

farmers and land managers, this means that soil temperature monitoring can provide a practical proxy for estimating vapor loss, enabling irrigation scheduling to align with cooler, less evaporative periods. Incorporating coupled heat-moisture dynamics into agro-hydrological models can improve forecasts of soil water availability and guide adaptive water allocation under variable climates.

(3) Texture-Specific Loss Patterns: Sandy soils sustain steady but high vapor losses, while clays, though slower to dry, release large amounts when cracking occurs. Management interventions must therefore be soil-specific: sandy soils benefit from barriers, mulches, or crust-forming agents, while clay-rich soils require crack-reducing practices such as organic matter additions, shallow tillage, or moisture-conserving mulches. Innovative approaches, such as sprayable biodegradable films, show promise for reducing losses by 20-30% [23].

(4) Climate and Season: In arid climates, midday losses dominate, whereas in humid or temperate zones, evaporation occurs more episodically. Adjusting irrigation timing to cooler, more humid periods can meaningfully reduce water loss, while mulching can promote nighttime condensation that returns small [24] but agriculturally valuable amounts of water to the soil profile. These strategies are particularly important as climate extremes intensify.

(5) Soil Amendments: Biochar reduces evaporation modestly (~10-11%) in sandy-loams [24], while clay additions to sandy soils improve retention but must be balanced to avoid cracking. This highlights that amendments should be selected not only for their water-holding benefits but also for their interactions with soil thermal regimes and cracking susceptibility.

(6) Monitoring Advances: New sensing technologies, such as fiber-optic humidity probes and isotopic tools, offer real-time insights into vapor dynamics [19, 25]. Integrating these tools into farm-level monitoring systems can support precision irrigation, early drought stress detection, and adaptive soil management, directly benefiting climate-smart agriculture.

(7) Model Integration: Current agro-hydrological models underestimate evaporation if vapor flow is ignored. Integrating vapor transport and dry soil layer dynamics into predictive tools will enable more accurate water budgeting and decision support [2], allowing farmers to optimize irrigation and reduce unnecessary water applications under increasing climate stress.

(8) Climate Change: Anticipated warmer and drier conditions will extend Stage-2 evaporation risks even into typically humid regions [4]. This underscores the urgency of adopting conservation practices—such as mulching, no-till farming, and organic amendments—not only in traditionally water-limited regions but also in areas previously considered water-secure.

(9) Research Needs: Field-based quantification of advective versus diffusive vapor flux, the role of pore-scale thermal feedbacks, and integration of soil heat-moisture processes into climate adaptation models remain pressing gaps. Addressing these will allow translation of experimental insights into actionable, climate-resilient agricultural strategies.

(10) Cross-Disciplinary Links: Heat transfer engineering and soil science share concepts—such as "evaporation buffers"—that could inspire new solutions in water conservation. Collaborations across engineering, agronomy, and environmental science can accelerate the development of novel, low-cost technologies for reducing evaporative losses.

Conclusion: Effective soil moisture management must be recognized as both a thermal and hydrological challenge. By adopting strategies informed by coupled heat-moisture dynamics, agricultural systems can conserve scarce water resources, improve irrigation efficiency, and build resilience against the intensifying impacts of climate change.

6. CONCLUSIONS

This review highlights that soil vapor transport is fundamentally governed by coupled heat-moisture dynamics. Temperature gradients and soil heat flux sustain evaporation well beyond the limits of simple diffusion, particularly during Stage-2 evaporation, where vapor movement becomes heat-limited. Rising soil temperatures and atmospheric demand therefore amplify water loss, making heat transfer a key driver of evaporation across agricultural soils.

Differences among soil types strongly shape evaporation pathways. Sandy soils in arid environments dry quickly, forming thick dry layers where vapor transport is enhanced by wind and pressure fluctuations. Clay soils, though initially resistant to drying, undergo rapid losses once heat-induced cracking develops, bypassing dry-layer resistance and accelerating vapor escape. Loam and silt soils exhibit intermediate behavior, where organic content and surface residues significantly influence retention and vapor movement. Across all soil types, substantial vapor loss occurs under hot conditions, confirming that management practices must be soil-specific.

Climate exerts an equally decisive role. Arid and semi-arid zones experience the greatest heat-driven vapor losses, while temperate regions see shorter, episodic effects tied to dry spells. Tropical soils, despite high ambient humidity, are also vulnerable to intense heating; however, practices such as mulching can recycle vapor through nighttime condensation and significantly reduce losses. With global warming expected to intensify soil heating even in wetter regions, strategies to mitigate vapor loss will become increasingly necessary across climates.

Recent experimental advances have deepened understanding of these processes. Fiber-optic humidity sensors, stable isotope tracing, and high-resolution humidity mapping now allow detailed tracking of evaporation fronts and vapor redistribution within soil layers. These insights reveal that conventional models underestimate evaporation in dry conditions. Coupled heat-vapor transport models, especially when accounting for surface mulch and residue effects, offer far more accurate predictions for drought and irrigation forecasting.

Overall, viewing vapor transport through the lens of heat transfer provides a unifying explanation for water losses across soil types and climates. This perspective underscores the importance of managing soil heating to reduce unproductive evaporation. The accumulated evidence up to recent studies offers both theoretical clarity and practical guidance, equipping agriculture with strategies to enhance water-use efficiency and build resilience in the face of climate variability.

7. RECOMMENDATIONS

For agricultural practice, farmers should prioritize soil mulching and covering as a frontline defense against evaporative losses. Organic residues, straw, biodegradable films, and plastics can reduce soil evaporation by 30-50%, with the choice of material adapted to climate and soil type. Plastic mulches are highly effective in arid regions where water scarcity is severe, while straw and crop residues perform better in temperate and tropical systems, where they simultaneously cool the soil and contribute organic matter. Even thin layers of mulch act as barriers to heat transfer and vapor diffusion, making them practical for diverse farming systems.

Equally important is optimizing irrigation timing and method. Water should be applied during cooler, high-humidity periods—typically at night or early morning—to minimize vapor pressure gradients. Drip and subsurface irrigation methods are preferable because they target the root zone and reduce surface evaporation. If surface irrigation is used, it should be followed by mulching or crusting to suppress the rapid losses typical of Stage-1 evaporation.

Building soil organic matter is another critical strategy. Incorporating compost, biochar, or cover crops improves soil structure, increases water retention, and slows evaporation. Biochar applications of 20-30 t/ha have been shown to be particularly effective in loams, while coarse biochar is better suited for sandy soils where rapid drainage and vapor loss are more severe. In heavy clay soils, preventing cracking is essential; timely irrigation before deep fissures form, shallow tillage, and the addition of fibrous organic matter or fine sand, combined with mulching, can minimize heat penetration and reduce vapor escape through cracks.

Conservation tillage practices such as no-till farming and the use of cover crops further enhance resilience. Crop residues left on the surface reduce midday soil temperatures by 1-3°C, significantly lowering evaporative demand, while off-season cover crops store water in their biomass and later serve as natural mulch. Monitoring tools should also be integrated into practice: soil temperature and humidity sensors provide early warnings of critical conditions, such as when temperatures exceed 35°C or relative humidity falls sharply. Linking sensor data to irrigation scheduling can ensure water is applied only when truly necessary, reducing waste.

For research and policy, future efforts must emphasize field trials across a wider range of climates. Multi-season experiments in tropical humid and continental temperate zones are especially needed to capture the full variability of evaporation, crop response, and water productivity. At the same time, models such as HYDRUS, SWAT, and APSIM must be refined to incorporate dry-layer vapor transport, soil heat dynamics, and mulch resistance. Translating these improvements into farmer-friendly decision-support tools will bridge the gap between scientific advances and practical adoption.

Innovation in materials also holds promise. Sprayable biodegradable polymers and cellulose-based films are emerging as alternatives to plastic mulches, offering sustainability benefits if proven effective and safe. Policy incentives can accelerate their uptake while reducing reliance on plastics. To support broad adoption, knowledge transfer must be strengthened through extension services, with findings communicated using farmer-friendly analogies—for example, describing mulch as a "lid on a pot" to illustrate its evaporative barrier function. Embedding these strategies within climate-smart agriculture programs can enhance their reach and impact.

Long-term monitoring systems are also vital. Combining ground-based sensors with thermal imagery and satellite observations will allow regional mapping of soil heat and evaporation dynamics under climate change, supporting both farmers and policymakers in anticipating risks. Finally, advancing cross-disciplinary collaboration between soil scientists, agronomists, and heat transfer engineers will foster novel approaches—from imaging techniques to evaporation control policies—that address desertification and water scarcity in a warming world.

In summary, integrating these practices with robust research and supportive policy can conserve soil water, improve yields, and build resilience against climate variability. Heat transfer science, when translated into practical soil management, offers a clear and actionable pathway to reduce unnecessary vapor losses and sustain agricultural productivity.

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NOMENCLATURE

h soil matric potential (or related humidity)
T temperature
K_{lh} hydraulic conductivities for liquid water flow due to gradients in pressure (isothermal liquid flow)
K_{lT} hydraulic conductivities for liquid water flow due to gradients in temperature (thermal osmosis)
t time
K_{vh} transport conductivities for water vapor flow due to humidity gradients (isothermal vapor diffusion)
K_{vT} transport conductivities for water vapor flow due temperature gradients (thermal vapor diffusion)

Greek symbol

θ volumetric water content (including liquid and vapor phases)