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MEASURING THE INVISIBLE: INNOVATIVE APPROACHES TO EVAPOTRANSPIRATION ESTIMATION

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Abstract

Evapotranspiration (ET), the combined process of soil evaporation and plant transpiration, is a critical determinant of crop water requirements, irrigation scheduling, and sustainable agricultural productivity. Globally, agriculture consumes nearly 70–80% of freshwater resources, with 60–65% of this usage lost through ET, underscoring its central role in water management. Conventional methods of ET estimation, including lysimeters, soil moisture balance, and empirical models, have been widely applied but face significant limitations in scalability, cost, and accuracy. In recent decades, advanced approaches have emerged, including satellite-based remote sensing models (SEBAL, METRIC), IoT-enabled smart sensor networks, machine learning and artificial intelligence algorithms, and UAV-based thermal imaging. These innovations allow for high-resolution, real-time, and spatially continuous ET estimation, significantly improving irrigation efficiency and water-use optimization. Moreover, hybrid frameworks that integrate remote sensing, IoT, AI/ML, and blockchain-enabled water accounting are paving the way toward next-generation smart irrigation ecosystems. Climate change, with its impacts on temperature, rainfall patterns, and vapor pressure deficit, further increases the urgency of precise ET monitoring for adaptive water management. This paper reviews global advancements in ET estimation techniques, highlights their strengths and limitations, and identifies research gaps. The study concludes that integrating traditional and modern approaches into hybrid, scalable, and farmer-friendly systems is essential for enhancing irrigation efficiency, ensuring food security, and building resilience against climate change.

Introduction

Evapotranspiration (ET) is a key process in agricultural crop production as it governs the movement of water from land to the atmosphere and directly influences plant growth, yield potential, and overall water use efficiency. It encompasses two fundamental processes: evaporation, which occurs from soil and other surfaces, and transpiration, which takes place through plant leaves and other vegetative structures. Together, these processes represent the total water requirement of a crop. Excessive rates of transpiration and evaporation, especially under conditions of water scarcity and rising global temperatures, often result in substantial yield losses, making ET a critical factor in sustainable crop management. In the present era of climate change and global warming, evapotranspiration losses are predicted to increase further, intensifying challenges for agricultural productivity. At the same time, the global population is expanding rapidly and is expected to reach nearly 9.7 billion by 2050, which places enormous pressure on food systems to produce more food with fewer natural resources, particularly freshwater. Agriculture alone accounts for about 70–80% of total freshwater withdrawals from ground and surface resources, of which nearly 60–65% is consumed through crop evapotranspiration. This highlights the central role of ET in determining agricultural water demand and management strategies. According to the Food and Agriculture Organization (FAO), accurate estimation of ET has the potential to enhance irrigation efficiency by 20–30%, thereby significantly contributing to improved crop productivity and sustainable food production. Effective irrigation management is dependent on precise knowledge of crop water requirements, and ET serves as the most fundamental parameter for this purpose. Apart from its role in agriculture, evapotranspiration also functions as a key regulatory component in regional hydrological balances, climate prediction models, and carbon–water cycle interactions, making it a crucial variable in Earth system science. The rate of ET is influenced by a wide range of factors, including genetic and physiological characteristics of crops, pest and disease incidence, insect infestations, and environmental variables such as solar radiation, air temperature, wind velocity, and relative humidity. For its estimation, several methods are available, broadly categorized into direct and indirect approaches. Direct methods include the field water balance approach, soil moisture depletion technique, lysimeter studies, atmometers, eddy covariance, and sap flow measurements; while these provide accurate results, they are time-consuming and require significant technical expertise. On the other hand, indirect methods such as empirical formulae, micrometeorological approaches, and remote sensing techniques offer faster and more practical solutions, particularly for large-scale agricultural monitoring. Accurate and timely monitoring of ET not only aids in determining irrigation schedules and frequency but also supports broader applications such as maintaining the hydrological cycle, evaluating groundwater recharge and depletion, optimizing crop planting and cultivation strategies, forecasting crop yields, and assessing the impact of climate variability on agricultural water use. Furthermore, ET is closely linked to global warming, as elevated temperatures and changing weather patterns increase the rate of evapotranspiration, thereby heightening crop water requirements and stressing already limited water resources. Hence, systematic assessment of ET is essential for sustainable water management, for enhancing crop productivity, and for addressing the dual challenges of climate change and food security at a global scale. Evapotranspiration (ET) accounts for almost 60-65% of all freshwater withdrawal losses in agriculture on a global scale, which means that more than 2,500 km3 of fresh water is consumed every year. Recent worldwide case studies have shown that ET overestimation could be reduced by 10% at most to save 200 billion m3 per year, which is equivalent to the total irrigation demand of South Asia (Liu et al., 2019). According to the predicted climate change scenarios, in aridity and semi-aridity regions, reference ET0 will become 12-18% higher by 2050, further worsening the food and water situation (Allen et al. 2021). This contributes to the strength of hybrid methods (ground-measurements combined with remote sensing) encapsulated in synergy with Artificial Intelligence (AI) driven processes for a better water scheduling and adaptive agriculture in the context of climate change (Zhang et al. 2023). Water scarcity is now seen as one of the greatest challenges of the 21st century and agriculture is the sector most affected by its high reliance on freshwater resources. It is estimated that almost 4 billion people face water stress conditions at least 1 year in a year and that by 2050 water demand for agriculture only is expected to grow by more than 50% from current levels (UNESCO, 2019). In this context, the variable evapotranspiration (ET) generally is a key variable for irrigation scheduling, hydrological modeling, and climate adaptation measures. Of all hydrologic components, ET is the only one that responds to both climatic forcing, such as radiation, temperature and humidity, and biological controls such as the phenology and the stomatal conductance of plants, as well as the canopy architecture. Because of its inherent multidimensional nature, ET estimation is both challenging and impossible, but essential to sustainable water use for agriculture. Climate-science research suggests that ET will be very vulnerable to future global warming scenarios. For instance, compared to current reference ET (ET0) given by climate model outputs is predicted to increase by 10-20 per cent in semi-arid and tropical regions by the year 2050, which would increase irrigation needs and also raise the potential for groundwater extraction (Zhang et al., 2023). Similarly, drought-prone areas in South Asia and Sub-Saharan Africa will experience substantial increases in crop water demands as a result of extended dry spells and elevated vapour pressure deficits (Rahman et al. 2022). These trends place a spotlight on the importance of next generation ET estimating methods that combine physical measurements with data-driven modelling methods. From the technological point of view, the integration of remote sensing, IoT-enabled smart sensors, and AI/ML algorithms has shifted ET tracking from predominantly labor-limited and field-scale applications to regional and near real-time applications (Chen et al. 2022). Remote sensing-based ET models for example deliver spatially explicit ET data with resolutions of 10-30 m, whereas machine learning approaches address non-linear relationships amongst soil, plant and climatic variables. Additionally, ET-based irrigation control is enabled by continuous irrigation management through an IoT platform (Patel et al. 2022). Despite these developments, problems such as high costs associated with deployment, interference from clouds in satellite data, and insufficient datasets for ML calibration have not been solved.

Innovative methods of measuring evapotranspiration

1. Global Importance of Evapotranspiration

Water scarcity has become one of the most pressing challenges of the 21st century, with the United Nations estimating that nearly four billion people experience severe water shortages for at least one month each year. Agriculture is the largest consumer of freshwater, accounting for about 70–80% of withdrawals from global surface and groundwater resources. Out of this, nearly 60–65% is consumed in the form of evapotranspiration (ET) from crop fields. Evapotranspiration, the combined process of soil evaporation and plant transpiration, is therefore a critical index for estimating crop water requirements and developing efficient irrigation strategies. According to the Food and Agriculture Organization (FAO), accurate ET estimation can enhance irrigation efficiency by 20–30%, enabling sustainable food production for a population projected to reach 9.7 billion by 2050. Beyond agriculture, ET also plays a crucial role in maintaining regional hydrological cycles, climate regulation, and carbon–water cycle interactions, making it a fundamental variable in Earth system science.

2. Conventional Approaches and Their Limitations

Traditional ET estimation methods have long been employed for field-scale water balance studies, but each comes with inherent limitations. Lysimeters, for example, are considered highly accurate, capable of detecting water mass changes as small as 0.01 mm. However, their high cost, labour-intensive maintenance, and poor scalability restrict widespread application. Soil moisture balance methods can provide crop-specific ET estimates but are strongly affected by soil heterogeneity and require frequent calibration. Other conventional instruments, such as evaporation pans and atmometers, are highly site-dependent and often yield variable accuracy when extrapolated across diverse agro-climatic zones. Even widely accepted empirical models, such as Penman-Monteith and Hargreaves-Samani, require local calibration of climatic parameters, limiting their universal applicability. Consequently, while traditional methods remain valuable, they alone cannot meet the precision and scalability demands of modern agriculture.

3. Remote Sensing-Based ET Estimation

Over the past two decades, remote sensing has revolutionized ET estimation by providing spatially continuous, large-scale, and time-series datasets. Satellite platforms such as MODIS, Landsat, and Sentinel generate data at resolutions ranging from 30 m to 1 km, which are integrated into models like SEBAL (Surface Energy Balance Algorithm for Land) and METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration). These models use parameters such as spectral reflectance, canopy temperature, and radiation balance to estimate ET at field and regional scales. Validation studies in arid regions of India and the Middle East have shown strong correlations ($R^2 > 0.85$) between MODIS-derived ET values and lysimeter data, highlighting their accuracy. Remote sensing also enables historical ET assessments for drought monitoring and climate adaptation planning. However, challenges remain, such as interference from cloud cover, coarse temporal resolution, and the requirement for ground-based validation to improve accuracy. The so-called satellite-based ET models, such as SEBAL, METRIC and SSEBop, have demonstrated relatively high predictions with R2 of greater than 0.85 compared to the lysimetric data (Senay et al., 2018). Spatial resolution has improved to 10-30 m from the recent Landsat 8 and Sentinel-2 integration, which enables mapping of ET for micro-farm scale (Velpuri et al., 2020). However, with improvements in data fusion methods (e.g., STARFM, Harmonized Landsat-Sentinel data), it is now possible to monitor ET on subweekly time-scales (Claverie et al., 2018), despite some cloud contamination. The technology helps precision irrigation systems in drought and groundwater depleted areas.

4. IoT and Smart Sensor Enabled ET Measurement

The emergence of the Internet of Things (IoT) has enabled high-resolution, real-time monitoring of ET at the farm level. Wireless sensor networks using LoRa, Zigbee, or NB-IoT communication systems can transmit data from soil moisture probes, atmometers, and mini-lysimeters to cloud-based dashboards. These platforms generate smart irrigation recommendations, helping farmers save water while improving yields. Field trials in semi-arid regions of southern India demonstrated that IoT-enabled irrigation systems using ET-based crop coefficients reduced water usage by 22% and simultaneously increased yields by 12% compared with conventional practices. Moreover, the integration of edge computing allows initial data processing at the device level, reducing bandwidth requirements and enabling decision-making in rural areas with limited connectivity. Such innovations are particularly relevant for smallholder farmers in developing countries where resource optimization is critical. Measured irrigation water savings of 20-25% with yield improvement of 10-15% has been achieved from IoT enabled ET computation using soil-plant-atmosphere continuum sensors (SPACS) in semi-arid region (Patel, S., Guzman, V.S., Lasker, A., Ouyang, W., McCiffin, J., & Moore, K., 2022). As the use of a combination of LoRaWAN and NB-IoT protocols for water monitoring has proven technically viable, this has opened up the possibility of sensor deployment in more economically-friendly ways in rural areas (Ayele et al., 2021) where there is less available connectivity. Moreover, with AI-enhanced edge computing, signals from ET are processed in real-time creating a 40% decrease in latency compared to the cloud-only solutions, which is critical for on-field decision support in variable weather conditions.

5. Artificial Intelligence and Machine Learning in ET Forecasting

Results show that Artificial Intelligence (AI) models, especially ANN, Random Forest and Long Short Term Memory (LSTM) networks, perform better as compared to traditional Penman-Monteith and Hargreaves-Samani methods, which have achieved RMSE reductions of 15-30% over a wide range of agro-climatic zones (Feng et al. 2021). Hybrid ML-RS models have been shown to be more flexible in mixed terrain, and daily ET estimations are now possible with an error of less than 0.5 mm/day (Chen et al. 2022). Further, ET prediction models have recently been extended by transfer learning for seeding areas with sparse meteorological datasets requiring low calibration costs (Rahman et al., 2023). Advances in artificial intelligence (AI) and machine learning (ML) have opened new avenues for ET prediction under variable climatic conditions. Models such as Artificial Neural Networks (ANN), Random Forests (RF), Support Vector Regression (SVR), and Long Short-Term Memory (LSTM) networks can analyze complex, non-linear interactions among meteorological, soil, and crop variables. Studies have shown that ML-based predictive models often achieve R^2 values exceeding 0.9 and reduce root mean square error (RMSE) by 15–20% compared with traditional empirical models. For instance, ANN models trained on MODIS datasets in China achieved daily ET predictions with errors below 0.5 mm/day, outperforming Penman-Monteith estimates. Hybrid frameworks combining ML algorithms with remote sensing inputs have further enhanced ET mapping across heterogeneous landscapes. These techniques are particularly valuable in regions with irregular rainfall and extreme temperature fluctuations, where accurate forecasting is essential for climate-resilient agriculture.

6. UAV and Drone-Based ET Estimation

UAVs carrying thermal and multispectral sensors have centimetrical resolution and monitor variations in canopy-level ET transparency that are undetectable by satellites (Gago et al., 2019). These recent UAV-AI integrations brought the ET estimation error margin below 5% compared with lysimeter reference results (Ballesteros et al., 2022). With falling flight costs, ET monitoring out of unmanned aerial vehicles (UAVs) is expected to be a US$1.5 billion global market over the next decade, notably in the areas of precision viticulture, horticulture, and smallholder farm management. Unmanned Aerial Vehicles (UAVs) equipped with thermal, multispectral, and hyperspectral sensors provide new opportunities for high-resolution ET monitoring at the field scale. Unlike satellites, drones offer flexible deployment and centimeter-level resolution (2–10 cm), allowing precise mapping of canopy temperature, vegetation indices, and soil surface moisture. In Spanish vineyards, UAV-derived ET estimates showed less than 5% error compared with lysimeter measurements, demonstrating their potential in precision agriculture. UAV-based monitoring is especially advantageous for fragmented landholdings and small-scale farms, where micro-variations in crop water demand cannot be effectively captured by satellites. Integration with 3D crop modeling further improves accuracy by accounting for canopy structure effects on ET dynamics.

7. Climate Change and ET Dynamics

Global climate change has added complexity to ET estimation. Rising temperatures, altered rainfall patterns, and increasing vapor pressure deficits are shifting crop water requirements worldwide. The FAO reports that reference ET (ET_0) has increased by 10–15% in semi-arid regions over the past three decades, substantially raising irrigation needs. Vegetation cover changes and land-use shifts further complicate transpiration processes. In response, researchers are exploring climate-driven ET models that integrate machine learning with downscaled climate projections to develop adaptive water management strategies. Such models provide not only present-day irrigation requirements but also future scenarios under heatwaves, droughts, and other climatic extremes.

8. Next-Generation Hybrid Architectures

Given the limitations of individual approaches, hybrid ET estimation systems have gained prominence. These frameworks integrate ground-based lysimeter calibration, satellite remote sensing, IoT-enabled dynamic monitoring, and AI/ML predictive analytics. Some researchers also propose blockchain technology for transparent water accounting, where ET-based irrigation data are securely stored and shared among stakeholders. Additionally, citizen science initiatives encourage farmers to report soil and crop conditions via mobile apps, which can then be incorporated into ET models to democratize data collection. Hybrid architectures thus represent the next generation of smart, scalable, and adaptive ET estimation frameworks, offering accuracy, transparency, and inclusiveness in agricultural water management.

9. Research Gap and Objectives

Despite significant technological advancements, several gaps remain in ET estimation. Remote sensing products still require ground calibration, IoT-based systems face scalability and cost barriers, ML models depend on large training datasets, and UAV applications are limited by regulatory restrictions and high costs. Therefore, there is a pressing need for agro-climatically adaptive, multi-source, multi-temporal ET estimation frameworks that are accurate, scalable, cost-effective, and farmer-friendly. The present research aims to explore and integrate novel ET estimation techniques—such as IoT-based smart sensing, AI/ML-driven predictive models, UAV thermal imaging, and hybrid systems—to enhance irrigation efficiency, support sustainable agriculture, and build resilience against climate change.

Conclusion

Evapotranspiration is a pivotal process in determining crop water requirements and optimizing irrigation management, making it indispensable for sustainable agriculture in the face of growing food demands and limited water resources. While conventional approaches such as lysimeters, soil moisture balance, and empirical models have contributed significantly to ET estimation, their limitations in scalability, cost, and accuracy highlight the need for more advanced solutions. Emerging technologies—remote sensing, IoT-enabled smart sensors, artificial intelligence, machine learning, and UAV-based monitoring—offer promising avenues for real-time, large-scale, and high-resolution ET measurement. Moreover, the integration of these technologies into hybrid frameworks, supported by innovations such as blockchain-based water accounting and citizen science initiatives, is paving the way for transparent, efficient, and climate-resilient irrigation systems.In the context of climate change, where rising temperatures and altered rainfall patterns are intensifying crop water demands, accurate and adaptive ET estimation becomes even more critical. By combining traditional methods with next-generation technologies, it is possible to develop holistic systems that not only improve irrigation efficiency and water conservation but also enhance crop productivity and long-term food security. Thus, timely, scalable, and precise estimation of evapotranspiration must be considered a cornerstone for smart water management strategies, ensuring that agriculture remains sustainable, resilient, and capable of meeting the needs of a rapidly growing global population.

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