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Revolutionizing Agriculture : Embracing the Era of Agriculture 4.0

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ABSTRACT

Agriculture significantly contributes to improving the livelihoods of disadvantaged communities, yet it also encounters challenges that impact both human well-being and the environment. Digital technologies can enhance this sector by lowering its environmental impact, conserving resources, fostering innovation, and creating economic opportunities. Agriculture 4.0 refers to the integration of innovations like precision farming, IoT, and big data to enhance production efficiency.

Keywords : Internet of things, Artificial intelligence.

Introduction

Agriculture is crucial for global socioeconomic development, maintaining food security and alleviating poverty and hunger (Sustainable Development Goals 1 and 2) (Pawlak and Ko³odziejczak, 2020). It also plays an important role in increasing employment opportunities, raising income levels, and improving the standard of living in underprivileged communities. However, agriculture faces significant challenges arising from unsustainable farming practices, which pose serious threats to both human well-being and the environment (FAO, 2017). Extensive crop cultivation has been a leading driver of deforestation and ecological degradation, resulting in the loss of natural habitats and a decline in biodiversity (Baste *et al.*, 2021). In the coming era, investing in digital technologies is essential to accelerate the transition to more sustainable agriculture systems to reduce the use of production inputs, minimise input costs, and preserve the environment (Mukherjee *et al.*, 2021). Digital technologies can upgrade the agriculture sector, reduce the environmental footprint, preserve natural resources, encourage entrepreneurial innovation, and provide economic opportunities (Araújo *et al.*, 2021). In this regard, in accordance with the FAO definition, Agriculture 4.0 is "a*griculture that integrates a series of innovations in order to produce agricultural products. These innovations englobe precision farming, IoT and big data in order to achieve greater production efficiency*". Agriculture

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4.0 is the latest step forward in Precision Agriculture, built on the idea of making farming more sustainable. This new revolution, which started in the early 2010s, combines technologies from Industry 4.0 with tools like sensors, robots, and artificial intelligence (AI), especially machine learning, to analyze data in smarter ways (Kovács and Husti, 2018). By connecting mobile devices and other digital platforms, Agriculture 4.0 creates and processes massive amounts of data to support better decision-making. The potential impact is high, it could boost productivity and efficiency in farming, improve the availability and quality of food, help adapt to climate change, cut down on food waste, and ensure natural resources are used more responsibly (Araújo *et al.* 2021). By focusing on these goals, Agriculture 4.0 has the power to transform farming while reducing its environmental footprint and tackling some of the biggest challenges facing global agriculture.

Agriculture 4.0 : How did it evolve?

Agriculture takes an integrated, holistic approach to agriculture, combining insights from biology, chemistry, economics, ecology, soil science, water science, pest management, and genetics. Its focus is on the improvement and management of the world's major food crops. Looking back (Figure 1), Agriculture 1.0 (The Era of Manual Labor, Pre-1950s) was characterized by simple tools, manual and animal labor, and a heavy reliance on natural elements like sunlight and rainfall. Farmers depended on their knowledge of the land, weather patterns, and traditional farming methods passed down through generations. This era was dominated by subsistence farming, where families produced just enough food to sustain themselves. Agriculture 2.0 (The Era of Mechanization, Chemical Fertilizers, and Agrochemicals, 1950s) brought significant changes, particularly the introduction of machinery that replaced manual labor and boosted productivity. This period also witnessed the development of chemical fertilizers and pesticides, which improved crop yields but led to negative environmental consequences. Agriculture 3.0 (The Era of Precision Agriculture, 1990s) embraced technology to optimize farming practices. GPS technology, remote sensing, and Geographic Information Systems (GIS) were integrated into farming operations to collect data on soil conditions, crop health, and weather patterns.

Key components

Agriculture 4.0 builds on the data sources and analytical platforms developed in Agriculture 3.0, with the convergence of technologies like the Internet of Things (IoT), artificial intelligence (AI), robotics, and big data analytics. Information management is crucial in Agriculture 4.0 (Figure 2), where various stages and elements come together in a seamless process. Sensors monitor the crops, generating data that is captured by a central platform. This data is then processed by specialized software and AI algorithms, which analyze it and offer potential intervention options. Based on these insights, the farmer decides how to act — either by directly using their own equipment or through automated machinery. This approach enhances decision-making and optimizes crop management. Key components include:

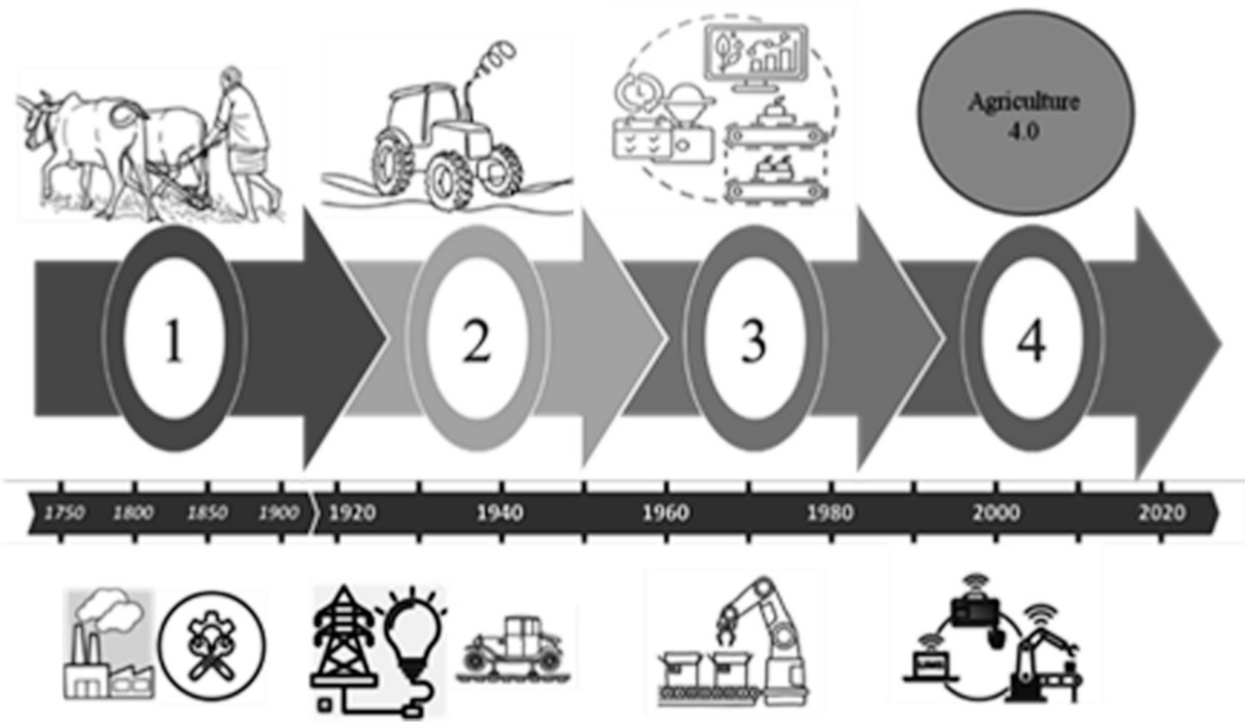

Fig. 1 : Evolution of Agriculture 4.0

Internet of Things (IoT) : IoT devices, such as soil sensors, weather stations, and smart irrigation systems, collect real-time data on soil moisture, temperature, and crop health, enabling farmers to make informed decisions and optimize resource use.

Artificial Intelligence (AI) : AI is used to analyze vast amounts of data from various sources, helping predict crop yields, detect diseases or pests, and optimize planting schedules. Machine learning algorithms can identify patterns to enhance farming decisions.

Robotics and Automation: Drones, autonomous tractors, and harvesters are employed to automate tasks such as planting, weeding, spraying, and harvesting, reducing labor costs and improving efficiency.

Big Data Analytics : The use of big data allows farmers to analyze large datasets from sensors, satellite imagery, and weather forecasts. This data-driven approach helps improve crop management, predict trends, and manage risks more effectively.

Precision Agriculture : Precision farming techniques utilize GPS, remote sensing, and GIS to apply inputs like water, fertilizer, and pesticides precisely where and when they are needed, minimizing waste and maximizing yields.

Blockchain : Blockchain technology ensures transparency and traceability in the supply chain, allowing consumers to verify the origin and quality of food products, and enhancing food safety.

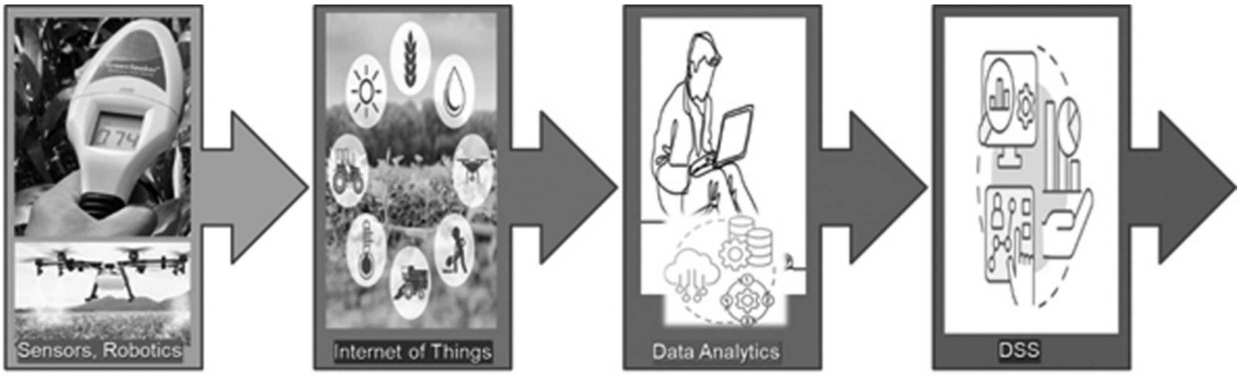

Fig. 2 : Core components of Agriculture 4.0

Challenges *cum* Opportunities

A systematic review by Gumbi *et al.* (2023) identified several key challenges and barriers preventing smallholder farmers from adopting Agriculture 4.0. These include issues related to the ownership and management of digital data and platforms (necessitating clear laws and regulations), the knowledge-capacity-willingness to adapt and adopt new technologies, and the need for business model innovation (such as adapting farming systems to incorporate robotics). Additional barriers include affordability concerns (both in terms of purchase price and operational costs) and the lack of adequate IT infrastructure to acquire, process, and share data effectively. As identified by Araújo *et al.* (2021), these challenges are categorized into five levels (device, data, network, application and system' Figure 3), each representing a key area for future research. Addressing these challenges would significantly enhance the viability and adoption of Agriculture 4.0 solutions, driving progress in the field.

Improving digital literacy and skills is crucial for overcoming these challenges. This can be achieved through access to timely, up-to-date data and information, creating awareness, shifting perceptions and behaviors, offering targeted training for older farmers, and understanding how digital solutions should be introduced to different farmer demographics. It's also important to assess farmers' current knowledge and attitudes toward technology and to include youth in agricultural education and training programs that focus on smart agriculture, business acumen, and technology integration.

Capacity building efforts must extend beyond current farmers, preparing youth — the future farmers by familiarizing them with new technologies during their schooling. As programming and robotics are increasingly included in high school curricula, there is an opportunity to steer students' interest in digital technologies toward agricultural applications. By fostering innovation and offering pathways for young people to engage with agricultural robotics, the sector can attract new talent and ideas, driving forward the digital transformation of agriculture.

The concept of Agriculture 4.0 is deeply tied to the use of Information and Communication Technologies (ICTs) and depends heavily on the availability of robust IT infrastructure to collect, process, and share data. For the system to function effectively, it requires continuous input of data, while farmers, farm managers, and operators must be able to control and process the data generated during operations and make informed decisions based on that information. This presents a significant challenge, especially in rural areas of developing countries, where mobile network coverage is often limited, and phone signals may not reach all farming regions. Without reliable connectivity, the full potential of Agriculture 4.0 cannot be realized, making it crucial to address the infrastructure gaps in rural areas.

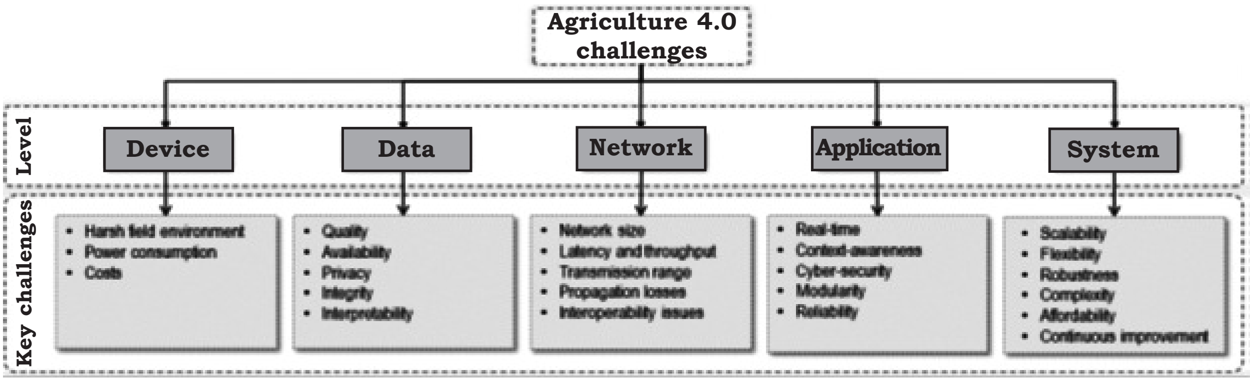

Fig. 3 : Agriculture 4.0: Understanding the challenges at five levels

Leveraging Remote Sensing and Machine Learning for Smart Irrigation Scheduling a Step Towards Agriculture 4.0 : A Case Study

Background

Irrigated agriculture uses over 70% of the world's freshwater (Foley *et al.*, 2011) and over 80% of the water in arid and semi-arid regions (Garrido *et al.*, 2010). With population growth and climate change, global water scarcity risk is projected to increase to over 56% by 2080 (Veldkamp *et al.*, 2016). Even though India has a population of 18% of the world, it only has enough water resources to support 4% of its citizen (Aayog, 2018). According to a recent report by the NITI Aayog, a significant portion of the country's population is experiencing severe water stress (Aayog, 2018). India is currently the largest consumer of groundwater globally. However, the situation is particularly concerning in three major regions, namely the north-western, western, and southern peninsular areas (groundwater in north-western India is being depleted @ 4 ± 1 cm yr^{-1}; Humphreys *et al.*, 2010). With more than 60% of irrigated agriculture and 85% of drinking water supplies dependent on groundwater, and growing industrial/ urban usage, groundwater resources come under increasing pressure (Jury and Vaux Jr, 2007). To mitigate water scarcity, manage droughts, and ensure sustainable water use, improving water productivity in agriculture is paramount. In the era of Agriculture 4.0, cutting-edge technologies like the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and remote sensing are revolutionizing resource management and agricultural productivity. A recent case study by Ghosh (2023) demonstrated how remote sensing and ML technologies can transform irrigation scheduling, paving the way for smarter water management and a more sustainable agricultural future. This study highlights the synergy between open-source satellite platforms, such as Landsat 8/9 and Sentinel-2, to retrieve frequent and accurate estimates of evapotranspiration (ET) and soil moisture. By employing Surface Energy Balance (SEB) models and the Optical Trapezoidal Model-based Evapotranspiration (OPTRAM-ET), the research demonstrated how remote sensing could monitor ET or crop water demand with high temporal frequency with reasonable accuracy. Concurrently, the study monitored root zone soil moisture stock by combining Landsat-derived spectral indices, surface soil moisture proxies, soil physical properties, and elevation data, processed through ML models. Integrating these satellite-derived ET estimates and root zone soil moisture stock into field water balance models enabled precise calculations of irrigation water requirements (IWR). This approach can help farmers determine the optimal timing and depth of irrigation, maximize water productivity, and establish a benchmark for sustainable irrigation practices, aligning with the vision of Agriculture 4.0.

Methodology

The study was conducted at the agricultural farms of the ICAR-Indian Agricultural Research Institute (IARI), New Delhi, during the *rabi* seasons of 2021–22 and 2022–23. Open-source satellite data from Sentinel-2 and Landsat 8/9 were utilized to retrieve evapotranspiration (ET) and root zone soil moisture.

Landsat 8/9 images were employed to estimate actual ET using six surface energy balance (SEB) algorithms: Surface Energy Balance Algorithm for Land (SEBAL), Surface Energy Balance Index (SEBI), Surface Energy Balance System (SEBS), Simplified Surface Energy Balance (SSEB), Simplified-Surface Energy Balance Index (SSEBI), and Two-Source Energy Balance (TSEB). The performance of these algorithms was evaluated to identify the most suitable one. Sentinel-2 images were used to estimate ET through the OPTAM-ET model proposed by Mokhtari *et al.* (2023). These two methodologies were used in synergy to estimate crop water demand of wheat at higher temporal frequency.

Water supply, in terms of root zone soil moisture stock, was characterized using Landsat 8/9 data by deriving multispectral indices, surface soil moisture proxies, in-situ soil physical properties (e.g., sand, silt, clay, field capacity, permanent wilting point, available water capacity), and elevation data. These inputs, along with observed profile soil moisture measured using a PR2 Probe (Delta-T device), were used to calibrate machine learning models, including Random Forest (RF), Cubist, and Gradient Boosting Machine (GBM). Model performance was assessed to identify the best-performing model.

A prototype for irrigation scheduling was developed by integrating evapotranspiration

(ET) and root zone soil moisture (RZSM) into the field water balance equation to determine irrigation water requirements and timing. The methodology is briefly illustrated in Figure 4, while detailed procedures are described in Ghosh (2023).

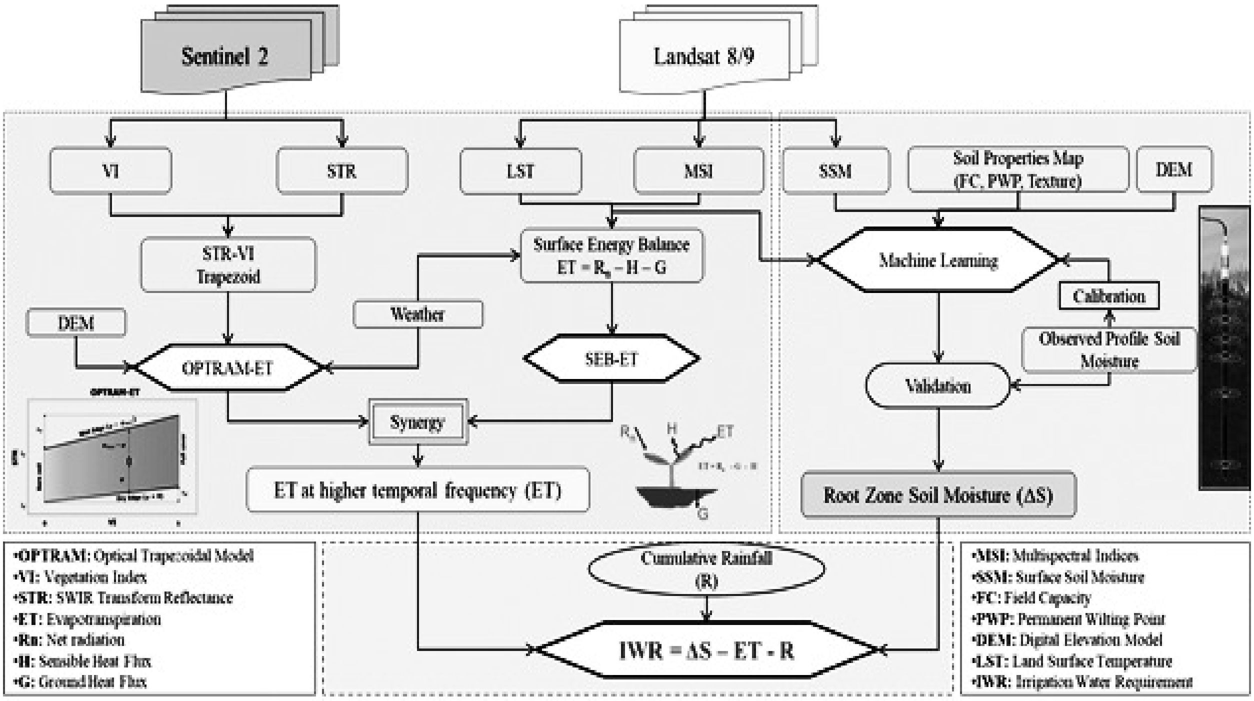

Fig. 4 : Workflow of the study summarizing the approach for farm-scale irrigation scheduling, aligned with the vision of Agriculture 4.0.

Findings

The SEBAL model found the best surface energy balance model to estimate ET using optical-thermal bands on the Landsat 8/9 satellite with an eight-day temporal frequency. To improve the frequency, the study utilized the Sentinel 2 satellite and another method called OPTRAM-ET, which only relies on optical bands to map the ET. Finally, the SEBAL model from Landsat 8/9 and the OPTRAM-ET model from Sentinel 2 were used together to improve ET monitoring with an average interval of five days (Figure 5).

The random forest and gradient boosting machine models were able to successfully capture the spatio-temporal variation of profile soil moisture from Optical-thermal (Landsat) remote sensing. The study reveals that satellite-derived spectral indices and dynamic variables have a significant impact on soil moisture up to 60 cm depth, indicating that remote sensing can be used for prediction of average profile soil moisture content (Figure 6).

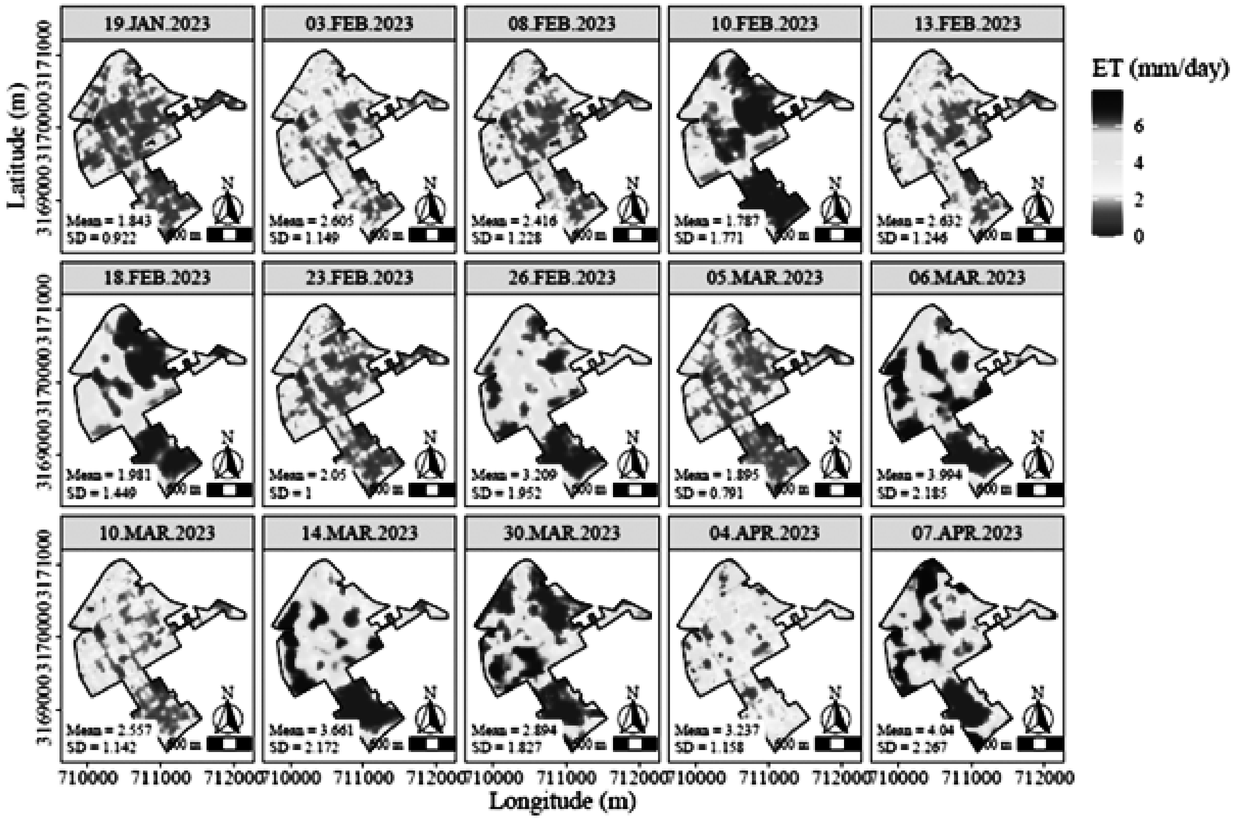

Fig. 5 : Evapotranspiration maps at higher temporal frequency

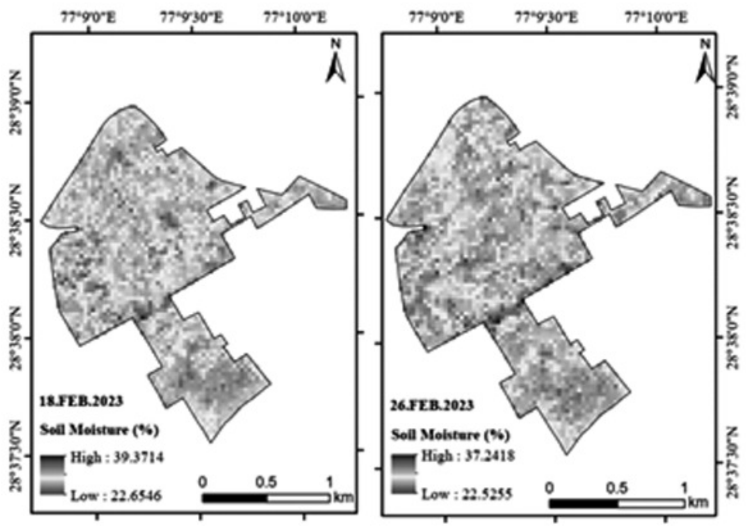

Fig. 6 : The profile soil moisture at 0-60 cm depth on 18th and 26th of February, 2023

By incorporating evapotranspiration and profile soil moisture data into a field water balance model, which uses multi-satellite estimates, this study has successfully identified irrigation events and accurately measured irrigation water requirements (IWR). The study has shown that remote sensing estimates are a highly effective tool for detecting irrigation events, leading to a significant reduction in water usage of approximately 36%. The amount of water needed to fill the root zone varies depending on the stage of the season. This study has combined ET and profile soil moisture from satellite estimates to quantify IWR at a spatial resolution of 30 m and an average temporal resolution of 5 days. The importance of open-source multi-satellite synergy for irrigation scheduling and water conservation has been aptly demonstrated.

Implications on Agriculture 4.0

The integration of opensource multi-satellite data (Landsat 8/9, Sentinel-2), advanced models (SEBAL, OPTRAM-ET), and machine learning techniques in this study exemplifies the transformative potential of Agriculture 4.0. By enabling precise, high-resolution monitoring of evapotranspiration (ET) and profile soil moisture, it supports optimized irrigation scheduling, reducing water usage and enhancing resource efficiency. This approach provides timely insights for decision-making, improves climate resilience, and fosters sustainable water management. Scalable and accessible through open-source technologies, it highlights how geospatial data fusion and predictive analytics can drive innovation, improve productivity, and promote sustainability in modern agriculture.

Conclusions

The global agricultural sector stands at the crossroads of innovation and necessity. Remote sensing and ML, as showcased in this study, provide a pathway toward sustainable water management, aligning with the principles of Agriculture 4.0. By leveraging these technologies, farmers can achieve precision in irrigation scheduling, conserve vital freshwater resources, and contribute to the resilience of global food systems. The integration of multi-satellite synergy and machine learning into farming practices is not just a technological advancement but a step toward a sustainable future.

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