COLLECTIVE STUDY OF COMPUTATIONAL FLUID DYNAMICS AND ARTIFICIAL INTELLIGENCE FOR SUSTAINABLE WATER MANAGEMENT IN THE AGRICULTURAL SECTOR

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Crossref DOI - https://doi.org/10.63665/rh.v7i2.55

Abstract :

Water scarcity, inadequate water storage, and inefficient irrigation practices continue to pose serious challenges to the agricultural sector, directly affecting crop productivity, farmer income, and food security. With the rapidly increasing demand for food and the growing stress on freshwater resources, there is a critical need for intelligent and adaptive water management systems that can optimise water usage while enhancing plant growth. In India, government initiatives in the distinct irrigation system have significantly improved irrigation efficiency; however, these technologies largely rely on static operating schedules and lack real-time, crop-specific decision-making capabilities. This study presents an integrated Artificial Intelligence (AI)–driven smart water management framework supported by Internet of Things (IoT)–based sensing and advanced Computational Fluid Dynamics (CFD) modelling for precision irrigation. The proposed closed-loop intelligent irrigation system minimises water wastage, prevents over-irrigation, improves nutrient uptake, and increases crop yield. This approach supports sustainable agriculture and aligns with national digital farming and smart agriculture initiatives.

Key Words : AI, IoT, Computational Fluid Dynamics (CFD), Digital farming and irrigation system.

Introduction :

Water is a fundamental resource for agricultural productivity, yet its availability is increasingly constrained by climate variability, population growth, rapid urbanization, and unsustainable water-use practices[1][2][3]. Agriculture alone consumes nearly seventy percent of global freshwater resources, making efficient and sustainable water management a critical priority for ensuring food security and long-term environmental stability. In countries such as India, where agriculture supports a large proportion of livelihoods, declining groundwater levels, erratic rainfall patterns, and insufficient water storage infrastructure pose serious challenges to crop production and farmer income[4][5]. Over the past few decades, significant progress has been made through the adoption of modern irrigation technologies, including sprinkler systems, drip irrigation, and micro-irrigation schemes promoted by government initiatives. While these systems have improved water-use efficiency compared to traditional flood irrigation, they largely depend on predefined schedules and uniform application strategies. Such static approaches fail to account for real-time variations in soil moisture, crop growth stages, root-zone dynamics, and short-term climatic conditions. Consequently, problems such as over-irrigation, water stress, nutrient leaching, and reduced yield potential continue to persist, limiting the effectiveness of existing irrigation practices[6]. Recent advancements in digital agriculture provide new opportunities to overcome these limitations. Artificial Intelligence (AI), when combined with Internet of Things (IoT)–based sensing, enables continuous monitoring, predictive analytics, and adaptive decision-making in irrigation management. However, many AI-based irrigation models rely primarily on data-driven correlations and lack integration with the underlying physical processes governing water movement in soil. In this regard, Computational Fluid Dynamics (CFD) offers a robust physics-based framework for simulating soil–water interactions, moisture transport, and root-zone water distribution with high spatial and temporal resolution[7][8]. This study presents a collective framework integrating CFD and AI to develop an intelligent, closed-loop water management system for agriculture. By coupling real-time sensor data with AI-driven optimization and CFD-based physical modelling, the proposed approach aims to enhance irrigation precision, reduce water wastage, and support sustainable agricultural practices in alignment with national smart farming initiatives[9]. Design model for Conceptual framework of Smart Irrigation Technology showing integration of monitoring systems, mobile/AI-based applications, and add-on sensors such as temperature, wireless networks, and soil moisture sensors for efficient irrigation management technology as shown in below Fig. (1)

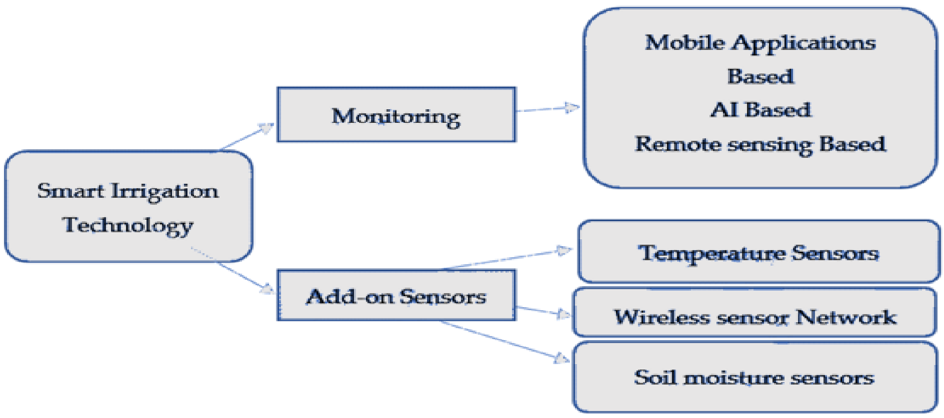

Fig. 1: Conceptual framework of Smart Irrigation Technology showing integration of monitoring systems, mobile/AI-based applications, and add-on sensors such as temperature, wireless networks, and soil moisture sensors for efficient irrigation management.

Methodology :

1. Data Acquisition Layer (IoT-Based Sensing) :

The data acquisition layer is responsible for continuous and real-time monitoring of field conditions using Internet of Things (IoT)–based sensors. Sensors are strategically deployed across the agricultural field at multiple soil depths to measure critical parameters such as soil moisture content, soil and ambient temperature, relative humidity, rainfall, and irrigation water flow rate. These sensors transmit data wirelessly to a centralized processing unit or cloud platform at regular intervals. This layer ensures reliable, high-resolution spatiotemporal data required for accurate irrigation assessment and decision-making[1][2].

2. Data Preprocessing and Feature Extraction :

Raw sensor data often contain noise, missing values, and inconsistencies due to environmental disturbances and sensor limitations. Therefore, data preprocessing is performed to improve data quality using noise filtering, outlier removal, interpolation, and normalization techniques. Subsequently, feature extraction is applied to derive meaningful indicators such as root-zone moisture deficit, evapotranspiration-related parameters, soil hydraulic properties, and crop growth stage indices. These features serve as structured inputs for the CFD simulations and AI-based prediction models[3][4].

3. CFD-Based Soil–Water Flow Modelling :

The CFD-based modelling layer simulates water movement within the soil by treating soil as a porous medium. Using governing equations for unsaturated flow, this module models infiltration, percolation, and moisture redistribution in the root zone. The soil domain is discretized, and appropriate boundary conditions representing irrigation input and drainage are applied. CFD simulations provide spatially resolved information on moisture distribution, water velocity, pressure gradients, and water loss zones, enabling a physics-based understanding of irrigation efficiency[5][6].

4. AI-Based Decision and Optimization Module :

The AI-based module utilizes machine learning and deep learning algorithms to predict crop water requirements and optimize irrigation strategies. It integrates real-time sensor data, CFD-derived features, weather information, and crop-specific parameters to estimate optimal irrigation timing, duration, and flow rate. The model continuously learns from historical data and system feedback, allowing adaptive and data-driven irrigation decisions that minimize water wastage while maintaining optimal soil moisture conditions for plant growth [7][8].

5. Control, Feedback, and User Interface Layer :

This layer executes irrigation decisions by sending control signals to actuators such as drip valves or sprinkler systems. Post-irrigation sensor data are collected and fed back into the system to evaluate irrigation performance and update AI models. A user-friendly web or mobile interface allows farmers to monitor real-time field conditions, review irrigation recommendations, and manually override system decisions if necessary. This closed-loop control mechanism ensures transparency, adaptability, and sustained irrigation efficiency[7][8][9]. Methods are summarized in Fig. (2).

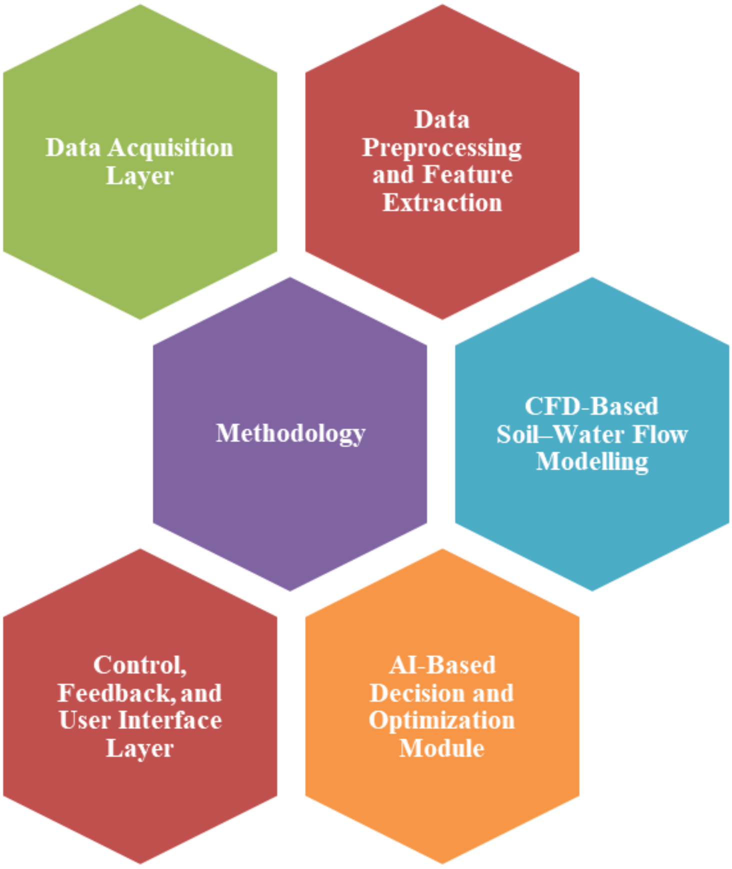

Fig. 2: Multi-layer architectural framework for AI and CFD-based smart irrigation system illustrating major components including Data Acquisition, Data Preprocessing and Feature Extraction, Methodology, CFD-based Soil–Water Flow Modelling, AI-based Decision and Optimization Module, and Control, Feedback, and User Interface Layer

Application :

1. Enhancement of Drip and Micro-Irrigation Systems :

Drip and micro-irrigation systems are widely recognized as efficient irrigation methods due to their ability to deliver water directly to the crop root zone with reduced surface runoff and evaporation losses[1]. However, in practice, many existing drip and micro-irrigation systems still operate using fixed, time-based irrigation schedules that do not account for dynamic variations in soil moisture, crop growth stages, root distribution, and changing climatic conditions. Such static operation often results in over-irrigation or under-irrigation, leading to inefficient water use, nutrient leaching, uneven moisture distribution, and sub-optimal crop performance. The proposed AI–CFD–based framework significantly enhances conventional drip and micro-irrigation systems by introducing adaptive, data-driven irrigation control. Real-time soil moisture data collected through IoT-based sensors provide continuous information on the actual moisture status within the root zone. These measurements are integrated with Computational Fluid Dynamics (CFD) modelling to simulate soil–water movement and moisture redistribution under different irrigation scenarios. By modelling soil as a porous medium, the CFD module captures infiltration, lateral movement, and deep percolation of water, enabling accurate assessment of how irrigation water spreads within the root zone[2][3] Fig. (3): Schematic representation of an intelligent irrigation system demonstrating automated water distribution through sensor-based control, drip and sprinkler mechanisms, and optimized irrigation management for different crop types.. The integration of CFD outputs with Artificial Intelligence (AI) algorithms enables precise regulation of irrigation flow rate and duration based on crop-specific water demand. Machine learning models analyse real-time sensor data, CFD-derived moisture distribution patterns, crop growth stage, and environmental conditions to determine optimal irrigation strategies[4]. Unlike conventional systems, irrigation is applied only when required and in quantities that match plant water uptake capacity, ensuring uniform moisture availability around the roots. This enhanced control mechanism significantly minimizes water losses due to deep percolation and evaporation, which are common issues in poorly managed micro-irrigation systems[5][6]. Moreover, precise water application reduces nutrient leaching beyond the root zone, thereby improving fertilizer use efficiency and maintaining soil fertility. The system also contributes to improved crop health and yield by preventing water stress and waterlogging conditions[7]. Overall, the AI–CFD–enabled enhancement of drip and micro-irrigation systems transforms traditional irrigation infrastructure into intelligent, self-adaptive systems. By optimizing water and nutrient use, reducing operational costs, and improving crop productivity, the proposed approach supports sustainable and precision agriculture, particularly in regions facing increasing water scarcity and resource constraints[8][9].

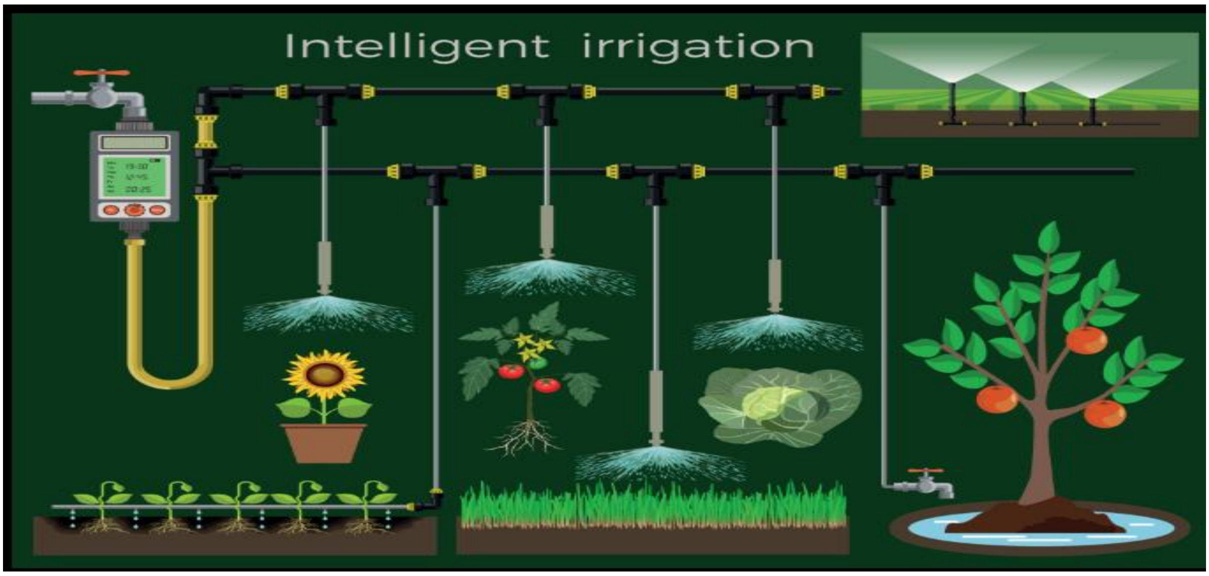

Fig. (3): Schematic representation of an intelligent irrigation system demonstrating automated water distribution through sensor-based control, drip and sprinkler mechanisms, and optimized irrigation management for different crop types.

2. Precision Irrigation Management :

Precision irrigation management is a key component of sustainable agriculture, aiming to deliver the exact amount of water required by crops at the appropriate time and location. Traditional irrigation practices often depend on fixed schedules or farmer experience, which do not adequately account for variations in soil properties, crop growth stages, root-zone dynamics, and changing climatic conditions. Such approaches frequently result in inefficient water use, leading to over-irrigation, runoff, deep percolation losses, soil nutrient leaching, and increased energy consumption. These inefficiencies not only reduce crop productivity but also place significant pressure on limited freshwater resources[1][2]. The proposed AI–CFD–based smart irrigation system addresses these limitations by enabling data-driven and adaptive precision irrigation. Real-time soil moisture sensors installed at different depths continuously monitor the moisture status within the crop root zone. These measurements are complemented by environmental data such as temperature, humidity, and rainfall, providing a comprehensive and accurate representation of field conditions. This real-time monitoring allows irrigation decisions to be based on actual crop water needs rather than generalized assumptions. A major advancement of the proposed system is the integration of Computational Fluid Dynamics (CFD) for modelling soil–water interactions. By representing soil as a porous medium, CFD simulations provide detailed insights into water infiltration, redistribution, and percolation processes occurring after irrigation. The spatial distribution of moisture within the root zone, water velocity profiles, and pressure gradients are accurately predicted, enabling identification of zones susceptible to water loss or insufficient wetting[3][4][5][6][7]. This physics-based understanding ensures uniform water distribution around plant roots and enhances irrigation effectiveness. Artificial Intelligence (AI) further strengthens precision irrigation by analysing real-time sensor data and CFD-derived features to predict crop-specific water requirements. Machine learning and deep learning models consider factors such as soil type, crop growth stage, historical irrigation patterns, and weather conditions to optimize irrigation scheduling. The AI model determines the optimal timing, duration, and flow rate of irrigation, ensuring that water is applied only when required and in the appropriate quantity. Through continuous feedback from post-irrigation sensor data, the system learns and adapts over time, improving prediction accuracy and system performance. The implementation of this precision irrigation management approach results in significant reductions in water wastage caused by runoff, evaporation, and deep percolation. At the same time, it maintains optimal soil moisture conditions that support healthy plant growth and efficient nutrient uptake. Additionally, optimized irrigation scheduling reduces pumping energy requirements and operational costs. Overall, the proposed precision irrigation management system enhances water-use efficiency, improves crop productivity, and contributes to sustainable agricultural practices, making it highly suitable for modern precision farming under conditions of increasing water scarcity and climate variability[8][9]. Diagrammatic representation is given below in the fig (4)

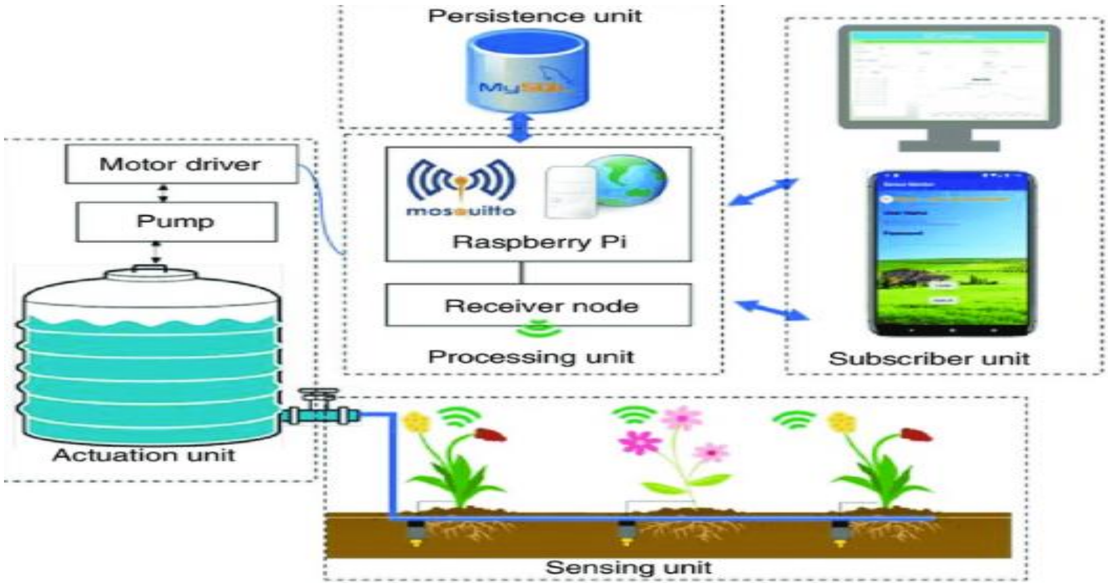

Fig. 4: Block diagram of an IoT-enabled smart irrigation system illustrating key components including sensing unit, processing unit (Raspberry Pi), data persistence unit, actuation unit, and subscriber interface for real-time monitoring and automated irrigation control.3.3 Decision Support System for Farmers:

3. Decision Support System (DSS) for Intelligent Irrigation Management :

A Decision Support System (DSS) plays a crucial role in modern precision agriculture by enabling farmers to make informed, timely, and data-driven decisions related to irrigation and water resource management. Traditional irrigation practices often rely on personal experience, fixed schedules, or visual assessment of crop conditions, which may not accurately reflect the actual water requirements of crops[1]. Such approaches can lead to inefficient water use, increased production costs, and reduced crop productivity. The proposed AI–CFD–based system addresses these challenges by incorporating an intelligent decision support framework through an integrated web and mobile interface [2]. The developed DSS provides real-time monitoring of critical field parameters, including soil moisture at multiple depths, ambient and soil temperature, relative humidity, rainfall, and irrigation system status. These real-time data are visualized through intuitive dashboards that allow farmers to continuously assess field conditions without physical presence in the field. This capability is particularly beneficial for large farms, remote agricultural areas, and regions facing labour constraints. By offering accurate and up-to-date field information, the DSS enhances situational awareness and reduces uncertainty in irrigation decisions. In addition to real-time monitoring, the DSS delivers AI-driven irrigation recommendations based on the analysis of sensor data, CFD-based root-zone moisture modelling, and crop-specific water requirements[3][4]. The system suggests optimal irrigation timing, duration, and flow rate, helping farmers apply water only when required and in appropriate quantities. These recommendations reduce over-irrigation and water stress, improve water-use efficiency, and ensure uniform moisture availability in the root zone. Farmers retain full control of the system, with the option to accept, modify, or override the suggested actions, thereby increasing trust and adoption of the technology[5][6]. The DSS also provides access to historical data and analytical insights, enabling farmers to evaluate long-term trends in water use, soil moisture variation, and crop response. Such historical analysis supports better planning of irrigation strategies across different crop growth stages and seasons. Furthermore, performance indicators such as water savings and irrigation efficiency can be used to assess the effectiveness of adopted practices and identify areas for improvement. Overall, the proposed decision support system empowers farmers with actionable insights and user-friendly tools, bridging the gap between advanced computational technologies and practical agricultural management. By promoting informed decision-making, reducing resource wastage, and enhancing crop productivity, the DSS supports technology-driven, sustainable farming practices and contributes to resilient agricultural systems under changing climatic and water availability conditions[7][8][9].

Conclusion and Future Scope :

This study presents an integrated AI–CFD–IoT–based framework for sustainable and precision water management in agriculture. By combining real-time sensing, physics-based soil–water flow modelling, and intelligent decision-making, the proposed system effectively overcomes the limitations of conventional irrigation practices. The integration of CFD provides detailed insight into root-zone moisture dynamics, while AI algorithms optimize irrigation timing, duration, and flow rate according to actual crop water requirements. As a result, the framework significantly enhances precision irrigation and drip/micro-irrigation systems by reducing water losses, preventing over-irrigation, improving nutrient uptake, and increasing overall water-use efficiency. The closed-loop architecture, supported by continuous feedback and a farmer-oriented decision support system, enables real-time monitoring and adaptive control, thereby promoting informed decision-making and technology-driven sustainable farming. The proposed approach is scalable and applicable to diverse agricultural settings, including open fields, greenhouses, and water-scarce regions. Future research can focus on large-scale field validation across different agro-climatic conditions and crop types to strengthen real-world applicability. Further enhancements may include the integration of nutrient transport modelling, advanced weather forecasting, reinforcement learning, and digital twin concepts to improve adaptive irrigation under climate variability. Overall, the proposed framework offers a promising pathway toward water-efficient, climate-resilient, and intelligent agricultural systems.

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