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Transition from open to closed-conduit irrigation systems: A comprehensive review

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Abstract

The global agricultural sector faces unprecedented pressure to maximize food production while drastically reducing water consumption, a challenge exacerbated by climate change and mounting water scarcity. Traditional open-conduit irrigation methods, such as canals and unlined ditches, are inherently inefficient, leading to substantial water losses through seepage, evaporation, and operational spillage. This review paper synthesizes current research concerning the transition from these traditional systems to modern closed-conduit systems, focusing primarily on micro-irrigation technologies like drip and micro-sprinklers. We examine the fundamental hydraulic design principles that underpin these pressurized systems, detail the substantial improvements in water use efficiency and crop productivity they facilitate, and conduct a sustainability assessment of their environmental impacts, particularly concerning water resource conservation. Furthermore, the paper provides a thorough overview of the integration of advanced digital technologies including Artificial Intelligence (AI) and the Internet of Things (IoT) for precise system management. Finally, we explore regional implementation challenges and adaptive strategies, arguing that the global shift towards closed-conduit infrastructure is an essential pathway for achieving long-term agricultural water security and resilience.

Keywords: Closed-conduit irrigation, precision agriculture, Artificial Intelligence, internet of things and sustainability

1. Introduction

Global agriculture accounts for approximately 70% of freshwater withdrawals, making efficient water management critical for ecological and human sustenance (Chouhan *et al.*, 2023) [7]. Historically, large-scale irrigation relied heavily on open-conduit systems gravity-fed networks of canals and laterals which, while effective for mass water delivery, are notoriously inefficient (Jain *et al.*, 2019) [10]. These methods are challenged by high conveyance losses, often resulting in significant depletion of streamflow and contributing to regional water stress in areas like the Western United States (Ketchum *et al.*, 2023) [12]. Furthermore, the reliance on large-scale infrastructure often overshadows the role of smaller, regional water bodies whose reactivation is now considered crucial for enhancing rice production sustainability and resilience (Li *et al.*, 2023) [16].

The imperative for water conservation, coupled with the need for enhanced crop yield and quality, has driven a paradigm shift towards closed-conduit (pressurized) irrigation systems (Ahmed *et al.*, 2023) [3]. This transition marks a fundamental technological leap from bulk water delivery to targeted, localized application. Closed-conduit systems, primarily micro-irrigation (e.g., drip and micro-sprinklers), deliver water directly to the plant root zone, minimizing losses and maximizing the control over water, nutrients, and energy inputs. This review provides a structured analysis of this monumental transition, exploring the engineering, performance, sustainability, and technological dimensions that define the future of water-secure agriculture.

1.1. Hydraulic Design Principles and Engineering Considerations in Closed-Conduit Systems

The shift to closed-conduit systems necessitates a robust understanding of hydraulic engineering principles, fundamentally replacing gravity-driven flow dynamics with pressurized flow analysis. Unlike open channels, closed systems such as pipelines rely on maintaining precise pressure heads across the network to ensure uniform water distribution to multiple outlets (Dawidowicz, 2018; Yıldırım, 2006) [8, 32]. The successful implementation of these systems depends on accurate design for both flat and sloping lands, requiring detailed calculations to minimize pressure variations that could compromise efficiency (Yıldırım, 2006) [32].

A critical consideration in this engineering transition is the energy requirement for operating the system, as pressure must be generated and maintained, often through pumping. Optimizing pump selection and characterization in pressurized irrigation systems, such as those found in central California, is essential for identifying potential energy savings and improving overall system economics (Pérez Urrestarazu & Burt, 2012) [25]. Furthermore, complex water distribution systems require sophisticated methods for evaluating the stability and reliability of pressure heads, which can be accomplished using advanced techniques like artificial neural networks (ANNs) for precise pressure zone management (Dawidowicz, 2018) [8]. The engineering integrity of the closed-conduit system thus directly translates into the field-level uniformity and efficiency that micro-irrigation promises.

2. Performance Evaluation

2.1. Water Use Efficiency

The most compelling argument for the transition to closed-conduit systems is the verifiable increase in both water use efficiency (WUE) and agricultural output. Drip irrigation, a prominent closed-conduit technology, delivers water directly to the root zone, significantly reducing non-productive water consumption and increasing the marketable yield of various crops (Yang *et al*., 2023) [30]. The targeted nature of water delivery is often combined with the precise application of fertilizer, known as fertigation, a practice proven to enhance crop productivity while improving nutrient delivery efficiency (Fanish *et al*., 2011) [9].

2.2. Crop Productivity Outcomes

Research across diverse crops confirms these benefits. For instance, studies on date palm demonstrated that deficit irrigation scheduling, made possible by the precision of closed systems, optimized water use without negatively impacting gas exchange, yield, or fruit quality (Mohammed *et al*., 2021) [20]. Similarly, in the production of summer maize, utilizing deficit drip irrigation based on crop evapotranspiration and precipitation forecasts led to marked improvements in water-use efficiency and grain yield (Lu *et al*., 2022) [17]. The flexibility of drip technology allows for advanced control over inputs, enabling researchers to determine optimal levels of water and nitrogen for maximizing the yield, quality, and water use efficiency of crops like potato (Akkamis & Caliskan, 2023) [4]. Beyond yield, the economic efficiency of drip irrigation, evidenced by investment profitability studies in regions like Egypt, further validates its superiority over traditional methods (Ali *et al*., 2020) [5]. For perennial crops like cotton, sound irrigation-water management, enabled by micro-irrigation, is key to boosting productivity and overall sustainability (Koudahe *et al*., 2021) [13]. Achieving precise application of water and fertilizer, while offering challenges, also presents considerable opportunities for future crop optimization (Xing & Wang, 2024) [29].

3. Sustainability Assessment

3.1. Water Resource Conservation

The sustainability benefits of closed-conduit irrigation systems are multifaceted, extending beyond farm-gate efficiency to encompass critical water resource and environmental stewardship. A central element is the measurable reduction in agricultural systems' water, energy, and food sustainability performance gaps (Zarei *et al*., 2021) [33]. The significant reduction in deep percolation and runoff characteristic of micro-irrigation helps to stabilize groundwater reserves, a critical global water cycle component whose changing nature is under intense scrutiny (Kuang *et al*., 2024) [14].

3.2. Environmental Impact Mitigation

The environmental benefits are particularly pronounced in mitigating nutrient pollution. By preventing excessive runoff and deep percolation, drip systems minimize the leaching of nutrients like nitrogen and phosphorus, thereby reducing the economic impact of nutrient pollution from agricultural waste (Sampat *et al*., 2021) [26]. This is increasingly important as climate change is projected to exacerbate the environmental impacts of agriculture globally (Yang *et al*., 2024) [31]. Furthermore, the precise control of water application can reduce risks associated with irrigating with marginal water sources, such as acid mine drainage-polluted soils, contributing to the agricultural sustainability of these vulnerable areas (Munyai *et al*., 2021) [23]. The move from open, evaporative, and runoff-prone systems to contained, targeted, and controlled delivery is thus foundational to fostering a more sustainable and resilient agricultural ecosystem.

4. Technological Innovations and Future Directions in Closed-Conduit System Management

The success of closed-conduit systems is becoming increasingly intertwined with the adoption of advanced digital technologies, leading to the emergence of "precision irrigation" (Adeyemi *et al*., 2017) [1]. This integration moves beyond simply pipe-and-drip hardware to sophisticated, data-driven system management. Artificial intelligence (AI) is at the forefront of this evolution, providing powerful tools for sustainable farming (Adewusi *et al*., 2024) [2]. AI algorithms are used for sensor data assimilation to estimate crop evapotranspiration and the crop water stress index, enabling real-time irrigation adjustments (Katimbo *et al*., 2023) [11]. AI models can predict optimal water and energy requirements for sensor-based micro-irrigation systems, even when powered by solar PV, facilitating a path toward energy-water nexus sustainability (Mohammed *et al*., 2023) [19]. While challenges remain, AI holds significant promise for improving irrigation management (Wei *et al*., 2024) [28].

The Internet of Things (IoT) provides the critical infrastructure for data collection and automation. IoT-based smart irrigation systems utilize embedded systems, telemetry data, and cloud computing to enhance water security and provide real-time control (Morchid *et al*., 2024, May; Morchid *et al*., 2024) [21, 22]. A systematic review highlights the increasing deployment of smart sensing technologies integrated with the IoT and AI across agriculture (Miller *et al*., 2025) [18]. Furthermore, solutions leveraging IoT sensors and machine learning techniques, such as Support Vector Machines (SVM), are being developed for intelligent, real-time irrigation (Kumar *et al*., 2024; Nsoh *et al*., 2024) [15, 24]. These technologies not only enable real-time water management but also facilitate precise application of water and fertilizer, addressing key challenges in crop nutrition (Xing & Wang, 2024) [29].

Further innovations include the use of blockchain technology to enhance transparency and security in precision irrigation, though this area presents unique implementation challenges (Bodkhe *et al*., 2022) [6]. Remote sensing technology offers broad-scale data for precision agriculture, providing essential information on crop health and water needs to complement the localized data from ground sensors (Sishodia *et al*., 2020) [27]. Collectively, these innovations transform closed-conduit systems into responsive, intelligent platforms capable of maximizing efficiency at unprecedented levels.

5. Case Studies and Regional Implementation: Challenges and Adaptive Strategies

While the benefits of the closed-conduit transition are globally recognized, regional implementation faces unique financial, social, and logistical challenges that require adaptive strategies. In India, for example, the transition is crucial given the country's vast and diverse agricultural landscape, but challenges related to small landholdings, lack of farmer awareness, and significant initial investment costs remain substantial barriers (Jain *et al*., 2019) [10]. Overcoming these issues often requires government subsidies and targeted educational programs to promote adoption of technologies like drip irrigation.

The investment required for transitioning from open-canal to pressurized, piped systems is often a major hurdle, particularly in developing economies. A study on the investment profitability of drip irrigation systems in Egypt provided evidence that while initial costs are high, the long-term economic efficiency and return on investment are favorable, making the financial outlay justifiable over time (Ali *et al*., 2020) [5]. This highlights a core adaptive strategy: framing the high initial capital expenditure not as a cost, but as an investment with guaranteed returns in water security, energy savings, and elevated crop yield.

Furthermore, the integration of new technologies requires significant upskilling of the farming community. The successful deployment of complex AI and IoT systems, such as those that use machine learning to predict water and energy needs (Mohammed *et al*., 2023) [19], depends on robust local support networks and simplified, user-friendly interfaces. Adaptive strategies must therefore include robust, continuous training programs that address the digital divide and ensure that the benefits of smart irrigation are accessible to all scales of agricultural producers (Ahmed *et al*., 2023; Wei *et al*., 2024) [3, 28]. The transition is thus a combined challenge of engineering, finance, and human capacity development.

6. Conclusion

The transition from open-conduit to closed-conduit irrigation systems represents one of the most critical transformations in modern agriculture. This comprehensive review underscores the profound benefits of this shift, driven by the escalating need for resource security and resilience. The foundational success of this transition lies in advanced hydraulic engineering, which enables the uniform distribution of water and provides opportunities for energy optimization. This technological leap yields measurable performance improvements, notably significant gains in water use efficiency, crop yield, and overall economic profitability across diverse crops. Crucially, the move to pressurized micro-irrigation is not merely an efficiency measure but a core sustainability strategy, actively mitigating environmental impacts by conserving streamflow, protecting groundwater, and reducing nutrient pollution. The future of closed-conduit irrigation is undeniably digital. The integration of AI, machine learning, and IoT forms an indispensable framework for precision agriculture, allowing for real-time, data-driven decisions that maximize the efficiency of water and fertilizer application. While regional complexities, such as financial constraints and technological gaps, persist, targeted policy interventions and educational programs can accelerate adoption. Ultimately, the widespread and successful implementation of intelligent, closed-conduit systems is the necessary prerequisite for achieving global food security in an era defined by climatic variability and finite water resources.

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