Sustainable water management for irrigated agriculture in Rwanda: systematic narrative review

Sonia Ikundabayo[1,2], Jean de Dieu Bazimenyera[1], Romuald Bagaragaza[1] & Jean Bosco Ngarukiyimana[3,4]

[1] Department of Civil, Environmental & Geomatics Engineering, University of Rwanda, Kigali, Rwanda

[2] Department of Civil Engineering, Rwanda Polytechnic, Musanze College, Rwanda

[3] Department of Ecotourism and Greenspace Management, University of Rwanda, Busogo, Rwanda

[4] Department of Forestry and Landscape Management, University of Rwanda, Busogo, Rwanda

Correspondence: Sonia Ikundabayo, Department of Civil, Environmental & Geomatics Engineering, University of Rwanda, Kigali, Rwanda. E-mail: isonia927@gmail.com

Submitted: December 19, 2025 DOI: 10.14295/bjs.v5i3.823
Accepted: February 25, 2026 URL: https://doi.org/10.14295/bjs.v5i3.823
Published: February 28, 2026

Abstract

Sustainable water management is fundamental to the performance of irrigated agriculture in Rwanda, where irrigation plays a critical role in food security, rural livelihoods, and national economic development. Over the past two decades, the Government of Rwanda has made substantial investments in irrigation infrastructure and policy initiatives, notably the Rwanda Irrigation Master Plan (RIMP) and the Strategic Plan for the Transformation of Agriculture (PSTA). Despite these efforts, irrigation coverage and water use efficiency remain below their estimated potential. Of the approximately 600,000 hectares considered suitable for irrigation, only about 10% is currently developed. This systematic narrative review synthesizes peer-reviewed and grey literature published between 2010 and 2025 to assess the status of irrigation systems, water management practices, institutional arrangements, environmental challenges, and emerging technological options in Rwanda. The review shows that around 148 irrigation schemes have been established across marshlands, hillsides, and valley bottoms; however, many schemes are constrained by underutilized infrastructure, sedimentation, high energy costs, limited farmer technical capacity, and weak operation and maintenance mechanisms. Surface irrigation remains the dominant practice, often associated with substantial water losses, while more efficient technologies such as drip and sprinkler systems demonstrate better performance but face low adoption due to financial and technical barriers. Integrated Water Resources Management (IWRM) is increasingly promoted as a guiding framework, emphasizing coordinated water allocation, social equity, and environmental sustainability. Nonetheless, persistent issues such as soil degradation, waterlogging, and inefficient resource use indicate gaps in governance, monitoring, and enforcement. Overall, the review highlights that achieving sustainable water management in Rwanda's irrigated agriculture will require strengthening institutional capacity, expanding farmer training, scaling up efficient irrigation technologies, and reinforcing IWRM implementation at catchment and scheme levels. These measures are essential for improving productivity, enhancing resilience to climate variability, and safeguarding long-term environmental sustainability.

Keywords: sustainable water management, irrigated agriculture, integrated water resources management (IWRM), Rwanda.

Gestão sustentável da água para a agricultura irrigada em Ruanda: Revisão narrativa sistemática

Resumo

A gestão sustentável da água é fundamental para o desempenho da agricultura irrigada em Ruanda, onde a irrigação desempenha um papel crucial na segurança alimentar, nos meios de subsistência rurais e no desenvolvimento econômico nacional. Nas últimas duas décadas, o Governo de Ruanda realizou investimentos substanciais em infraestrutura de irrigação e em iniciativas de políticas públicas, notadamente o Rwanda Irrigation Master Plan (RIMP) e o Strategic Plan for the Transformation of Agriculture (PSTA). Apesar desses esforços, a cobertura da irrigação e a eficiência no uso da água permanecem abaixo do potencial estimado. Dos aproximadamente 600.000 hectares considerados adequados para irrigação, apenas cerca de 10% estão atualmente desenvolvidos. Esta revisão sistemática sintetiza literatura revisada por pares e literatura cinzenta publicada entre 2010 e 2025, com o objetivo de avaliar a situação dos sistemas de irrigação, as práticas de gestão da água, os arranjos institucionais, os desafios ambientais e as opções tecnológicas emergentes em Ruanda. A revisão mostra que cerca de 148 projetos de irrigação foram estabelecidos em áreas de pântanos, encostas e fundos de vale; contudo, muitos desses sistemas enfrentam limitações como infraestrutura subutilizada, assoreamento, altos custos de energia, capacidade técnica limitada dos agricultores e mecanismos frágeis de operação e manutenção. A irrigação por superfície permanece como a prática predominante, frequentemente associada a perdas significativas de água, enquanto tecnologias mais eficientes, como os sistemas de gotejamento e aspersão, apresentam melhor desempenho, mas enfrentam baixa adoção devido a barreiras financeiras e técnicas. A Gestão Integrada de Recursos Hídricos (GIRH) é cada vez mais promovida como estrutura orientadora, enfatizando a alocação coordenada da água, a equidade social e a sustentabilidade ambiental. No entanto, problemas persistentes como degradação do solo, encharcamento e uso ineficiente dos recursos indicam lacunas na governança, no monitoramento e na fiscalização. De modo geral, a revisão destaca que alcançar a gestão sustentável da água na agricultura irrigada de Ruanda exigirá o fortalecimento da capacidade institucional, a ampliação da capacitação dos agricultores, a expansão de tecnologias de irrigação mais eficientes e o reforço da implementação da GIRH nos níveis de bacia hidrográfica e de projeto. Essas medidas são essenciais para melhorar a produtividade, aumentar a resiliência à variabilidade climática e garantir a sustentabilidade ambiental de longo prazo.

Palavras-chave: gestão sustentável da água, agricultura irrigada, gestão integrada de recursos hídricos (GIRH), Ruanda

1. Introduction

Agriculture remains the backbone of Rwanda's economy, making a significant contribution to food security, employment, and rural livelihoods. The sector employs over 70% of the population and contributes nearly one-third of the national Gross Domestic Product (GDP) (Heinen et al., 2022; NISR, 2023). Beyond its economic role, agriculture is crucial for poverty reduction and social stability, particularly in rural areas where smallholder farming dominates (Bird et al., 2022). Despite this importance, agricultural productivity in Rwanda remains constrained by structural and environmental challenges (Perez et al., 2023).

Rwandan agriculture is predominantly rain-fed and therefore highly vulnerable to erratic and increasingly unpredictable rainfall patterns. Recurrent droughts, prolonged dry spells, and shifts in seasonal rainfall have led to frequent crop failures, reduced yields, and unstable farm incomes. These challenges are further exacerbated by the country's hilly topography, which complicates water control, accelerates soil erosion, and increases runoff losses. As a result, effective water management has become essential for achieving sustainable agricultural growth and resilience to climate variability (Lydie et al., 2022).

In response, the Government of Rwanda has placed irrigation development at the center of its agricultural transformation agenda (Booth et al., 2014). Key policy instruments, including the Rwanda Irrigation Master Plan (MINAGRI, 2010; RAB, 2020; CIFOR-ICRAF, 2020) and the Strategic Plan for the Transformation of Agriculture (MINAGRI, 2018), emphasize the expansion of irrigated land, improved water use efficiency, and enhanced climate resilience within agricultural systems (Mabhaudhi et al., 2025). These efforts are further reinforced by broader national frameworks such as Vision 2050, which prioritizes increased agricultural productivity, food security, and irrigation development as drivers of long-term economic growth. Complementary policies, including the Land Use Master Plan and the National Irrigation Policy and Strategy, guide land allocation and promote sustainable and efficient use of water resources across agricultural landscapes (Bizoza et al., 2021).

Irrigation plays a critical role in stabilizing agricultural production, particularly in regions where rainfall alone cannot meet crop water requirements (Gebremedhin et al., 2023). However, the effectiveness of irrigation systems depends not only on water availability but also on the quality of irrigation water, management practices, and the condition of supporting infrastructure (Levidow et al., 2014). Poorly managed irrigation can lead to soil degradation, salinization, and declining crop productivity, thereby undermining the intended benefits of irrigation investments (Rengasamy, 2018).

Although Rwanda is estimated to have an irrigation potential of nearly 600,000 hectares, only about 10% of this area has been developed to date. Consequently, many rural households, especially smallholder farmers with limited landholdings, remain highly food insecure and vulnerable to climate-related shocks (Hakiruwizera et al., 2022). To date, approximately 148 irrigation schemes have been established across marshlands and hillsides. Nevertheless, the performance of many of these schemes remains suboptimal, characterized by low water use efficiency, underutilized infrastructure, and modest productivity gains. In several cases, dams, conveyance systems, and on-farm irrigation networks are poorly operated and maintained, partially functional, or entirely abandoned (Tuyisabe et al., 2024).

Despite significant public investment and institutional reforms, irrigation performance and water management efficiency in Rwanda continue to fall short of their potential. National and international assessments identify persistent challenges, including inadequate maintenance, sediment accumulation in canals, limited farmer technical capacity, high energy costs, weak extension support, and insufficient technical oversight (FAO, 2017; World Bank, 2021). Fragmented landholdings and weakly organized water user associations (WUAs) further constrain collective action and effective scheme management.

This review examines sustainable water management strategies for irrigated agriculture in Rwanda, with a particular focus on improving irrigation performance, enhancing water use efficiency, and reducing environmental impacts. By synthesizing existing evidence, the study seeks to strengthen understanding of the linkages between irrigation water management, agricultural productivity, and environmental sustainability, thereby informing policy and practice toward more resilient and sustainable irrigated agriculture in Rwanda.

2. Materials and Methods

2.1 Study design

This study adopted a systematic narrative review approach to synthesize existing evidence on sustainable water management strategies in irrigated agriculture in Rwanda. The review was conducted in accordance with the PRISMA 2020 guidelines to ensure transparency, reproducibility, and methodological rigor. A systematic narrative review is appropriate when included studies exhibit substantial heterogeneity in research design, outcome measures, analytical techniques, and contextual settings, making quantitative meta-analysis unsuitable. Given the diversity of empirical, modeling, technical, and policy-oriented research in irrigation and water management, findings were integrated using a structured qualitative thematic synthesis. The review process followed four sequential stages: identification, screening, eligibility assessment, and narrative synthesis.

2.2 Data sources

A comprehensive literature search was conducted to capture peer-reviewed and institutional publications relevant to irrigation and water management in Rwanda. Electronic databases searched included Scopus, Web of Science (WoS), PubMed, CAB Abstracts, and ScienceDirect to ensure broad academic coverage. In addition, institutional and policy documents were retrieved from official sources, including the Ministry of Agriculture and Animal Resources (MINAGRI), the Rwanda Agriculture and Animal Resources Development Board (RAB), and the Rwanda Water Resources Board (RWB). Reports from international organizations such as the Food and Agriculture Organization (FAO), the World Bank, and the International Water Management Institute (IWMI) were also consulted to strengthen contextual and technical analysis.

2.3 Search strategy and keywords

A structured search strategy was applied using predefined keywords combined with Boolean operators (AND, OR) to systematically retrieve relevant literature published between 2010 and 2025. Core search terms included combinations of “irrigated agriculture,” “water management,” “integrated water resources management (IWRM),” “irrigation systems,” “irrigation efficiency,” “water use efficiency,” “environmental impacts of irrigation,” “climate-smart agriculture,” and “water management policy frameworks,” with a primary focus on Rwanda. Where Rwanda-specific evidence was limited, studies from comparable agro-ecological and institutional contexts within East Africa were included to enhance interpretative depth and comparative insight.

2.4 Inclusion and exclusion criteria

Studies were included if they addressed irrigation development, irrigation performance, agricultural water management practices, water use efficiency, environmental sustainability, or institutional and policy frameworks relevant to agricultural systems. Priority was given to studies conducted in Rwanda or comparable East African agro-ecological zones, published in English between 2010 and 2025, and presenting sufficient methodological detail to support critical assessment. Studies were excluded if they focused exclusively on non-agricultural water sectors such as urban or industrial water management, were opinion-based without analytical rigor, duplicated existing records, or demonstrated limited relevance to irrigation water management in the Rwandan context.

2.5 Types of studies included

To capture the multidimensional nature of irrigation water management, the review incorporated diverse study designs. These included experimental field evaluations of irrigation technologies, observational studies such as surveys and case studies, modeling and simulation research related to irrigation scheduling and water balance, technical and project evaluation reports, and institutional and policy analyses. This inclusive approach enabled integration of biophysical, technical, socio-economic, and governance dimensions of irrigation sustainability.

2.6 Study selection process

The study selection process followed the PRISMA 2020 framework to ensure methodological transparency. An initial search identified 680 records from electronic databases, with 12 additional records retrieved from institutional repositories and other sources. After removing 120 duplicate records, 572 studies remained for title and abstract screening. Of these, 400 records were excluded due to a lack of relevance to irrigation development, water management practices, or sustainability outcomes. Full-text assessment was conducted for 172 potentially eligible studies, resulting in the exclusion of 82 articles due to insufficient methodological clarity or contextual relevance. A total of 90 studies were included in the final qualitative synthesis. The selection process is illustrated in the PRISMA 2020 flow diagram (Figure 1), ensuring traceability and transparency.

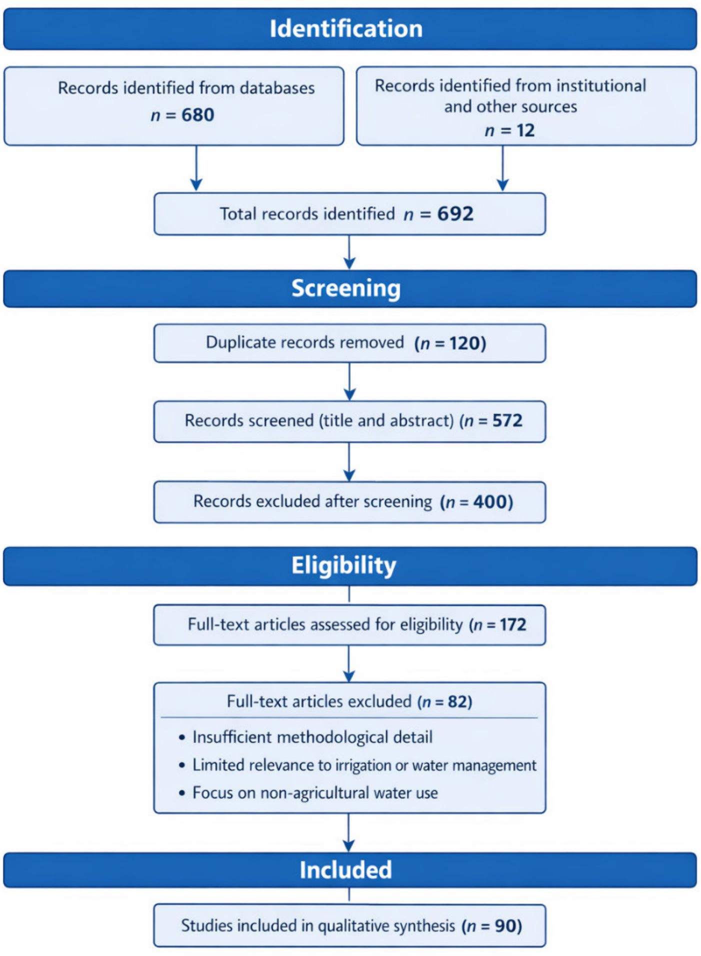

Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility, and inclusion of studies in the systematic review of sustainable water management for irrigated agriculture in Rwanda. Source: Authors, 2025.

2.7 Methodological quality assessment and risk of bias

To enhance the reliability and validity of the synthesis, included studies were critically appraised using predefined quality evaluation criteria. Assessment focused on clarity of research objectives, appropriateness of study design, adequacy of data sources, analytical rigor, transparency of assumptions, and contextual relevance to irrigation water management in Rwanda. Studies were categorized as high, moderate, or low methodological quality. Findings from studies with methodological limitations were interpreted cautiously within the narrative synthesis, and studies demonstrating substantial risk of bias or insufficient methodological transparency were excluded during eligibility assessment.

2.8 Data synthesis and analysis

Data synthesis was conducted using a structured thematic narrative approach. Findings from the selected studies were systematically coded and grouped into key thematic domains, including irrigation systems and development trends, water management practices and efficiency, environmental and sustainability challenges, institutional and policy frameworks, and technological innovations. Evidence across studies was compared, integrated, and critically interpreted to identify patterns, consistencies, and divergences. This approach enabled the development of a comprehensive understanding of how irrigation water management influences agricultural productivity, climate resilience, and environmental sustainability in Rwanda.

3. Results

3.1 Current status, potential, and operational challenges of irrigation systems in Rwanda

Rwanda's irrigation infrastructure extends across marshlands, hillsides, and valley-bottom areas, with varying levels of development and functionality (Tuyisabe et al., 2024). National assessments show that irrigation potential is primarily derived from marshlands (222,418 ha^{-1}), runoff harvested in small reservoirs (125,627 ha^{-1}), lake water resources (100,153 ha^{-1}), direct river and floodwater abstraction (80,974 ha^{-1}), groundwater resources (36,434 ha^{-1}), and runoff stored in dams (31,204 ha^{-1}) (Hakiruwizera et al., 2022) (Figure 2).

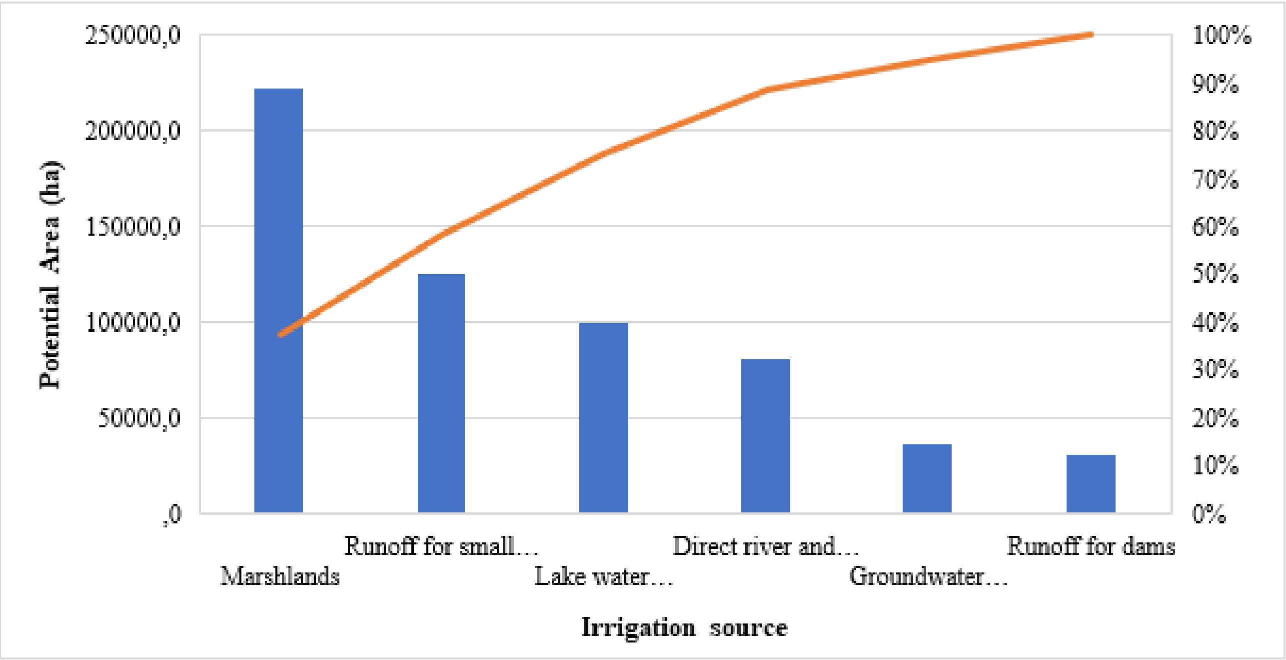

Figure 2. Rwanda's irrigation potential. Source: Authors, 2026. Source: Adapted from Hakiruwizera et al. (2022). The data represent the estimated national irrigation potential by water source category. The figure was constructed by the authors using aggregated secondary data reported in the cited study. Values were compiled and visualized using Microsoft Excel (Version 2020), with proportional representation calculated based on total estimated irrigation potential.

Despite this considerable potential, the actually developed and effectively utilized irrigated area remains limited. Many schemes operate below design capacity due to structural and managerial constraints. Common challenges include underutilized storage facilities, deterioration of conveyance and field distribution networks, and fragmented landholdings that complicate coordinated scheduling and water allocation. These constraints reduce overall system reliability and limit production outcomes, particularly for smallholder farmers dependent on shared infrastructure (Mabhaudhi et al., 2025).

Empirical evidence suggests that schemes with functional infrastructure and organized management structures achieve more consistent production cycles and higher cropping intensity. However, national-level assessments indicate a gap between installed infrastructure and effective service delivery. The continued predominance of gravity-based surface systems reflects earlier investment approaches and cost considerations, but these systems often operate below optimal performance levels when maintenance and management are insufficient (Celestin et al., 2023). Overall, while Rwanda has expanded irrigation infrastructure over recent years, strengthening operational performance and ensuring full utilization of developed schemes remain critical priorities.

3.2 Types of irrigation systems used in Rwanda

Rwanda utilizes several irrigation methods adapted to its diverse topography and varying water availability. The principal systems include surface irrigation, sprinkler irrigation, and drip irrigation. Surface irrigation is the most widely practiced method, particularly in marshlands and valley-bottom areas where gravity-fed systems are feasible. This approach includes furrow, basin, and border irrigation techniques, which together account for approximately 49.7% of irrigated plots. Traditional uncontrolled flood irrigation represents about 41% of irrigated areas (Mukanyandwi et al., 2018; Mabhaudhi et al., 2025; Hakiruwizera et al., 2022).

Sprinkler irrigation is applied mainly on hillsides and medium- to large-scale farms. In eastern regions characterized by relatively flat terrain and consolidated land parcels, center-pivot systems are increasingly implemented. In contrast, fixed sprinkler systems are more common in smaller or localized schemes. Sprinkler systems account for approximately 6.7% of irrigated land (Mabhaudhi et al., 2025). Drip irrigation systems, which distribute water through networks of pipes and emitters directly to the plant root zone, represent about 2.5% of irrigated areas. These systems are typically introduced in high-value crop production and controlled irrigation environments (Gaspard et al., 2023).

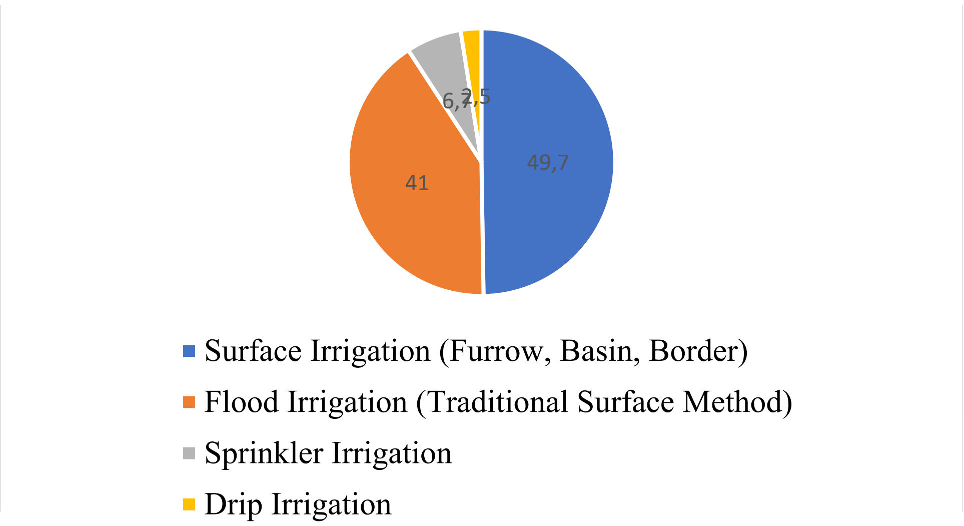

Figure 3. Distribution of irrigation systems in Rwanda (% of irrigated area). Source: Compiled from Mukanyandwi et al. (2018), Hakiruwizera et al. (2022), and Mabhaudhi et al. (2025). Percentages represent reported national estimates of irrigated area under different irrigation methods. The figure was constructed by the authors using aggregated secondary data and visualized using Microsoft Excel (Version 2020). No additional statistical transformation was performed beyond proportional representation.

3.3 Scale of irrigation practices

Irrigation in Rwanda operates across small, medium, and large-scale systems, each characterized by distinct technological and management features. Small-scale irrigation, typically covering 0.1–10 ha^{-1}, relies on complete drip or sprinkler kits, rain-gun systems, motorized or solar pumps, and rainwater harvesting structures. In 2020, small-scale irrigation covered approximately 17,689 ha^{-1}, reflecting its growing importance for household-level food security and income diversification (Jones et al., 2022; Maniriho et al., 2022).

Medium-scale irrigation schemes (10–100 ha^{-1}) are predominantly located in marshlands and hillside areas and often involve collective management arrangements. Large-scale irrigation systems, exceeding 100 ha^{-1}, are generally mechanized and concentrated in maize-producing areas. National statistics indicate that approximately 9.2% of farmers practice irrigation, with small-scale farmers forming the majority of irrigators, while large-scale schemes account for a disproportionately higher share of irrigated land (Ngango; Hong, 2021; Tuyisabe et al., 2024). This distribution underscores persistent inequalities in access to irrigation infrastructure and capital, with implications for productivity, equity, and resilience.

Table 1. Scale of Irrigation Systems in Rwanda.

Scale of Irrigation	Area (ha^{-1})	Typical Technologies / Methods	Key Features	References
Small-scale	0.1 – 10	Drip, sprinkler kits, rain-gun systems, motorized/solar pumps, rainwater harvesting	Household-level, food security & income diversification; the majority of farmers	Jones et al., 2022; Maniriho et al., 2022
Medium-scale	10 – 100	Surface & sprinkler irrigation; collective management	Marshlands & hillside areas; shared management; moderate productivity	Ngango; Hong, 2021; Tuyisabe et al., 2024
Large-scale	>100	Mechanized sprinkler & pivot systems	Focused on high-value crops (e.g., maize), high productivity, and fewer farmers	Ngango; Hong, 2021; Tuyisabe et al., 2024

Source: Authors, 2025.

3.4 Water management practices and efficiency

Climate variability continues to affect water availability for agriculture, reinforcing the importance of effective irrigation management (Smith et al., 2010). However, the continued reliance on traditional surface irrigation methods limits overall system performance. Sediment accumulation in canals, inadequate operation and maintenance, and limited technical skills at the scheme level further reduce efficiency (FAO, 2017; World Bank, 2021).

While sprinkler and drip systems have been introduced in several schemes, their adoption remains constrained by financial limitations and insufficient technical support. As a result, water productivity in many irrigation schemes remains below national expectations. Improving performance, therefore, requires a combination of technological modernization, strengthened operation and maintenance practices, farmer capacity development, and improved institutional coordination to ensure equitable and efficient water allocation (Mukanyandwi et al., 2018).

3.5 Environmental impacts of irrigation in Rwanda

While irrigation development has increased productivity and supported the commercialization of hillside farming, particularly under the Land Husbandry, Water Harvesting, and Hillside Irrigation (LWH) Project, it has also resulted in environmental challenges. Project documentation identifies potential direct impacts on soil and hydrological systems, including disruption of drainage patterns, loss of soil and vegetation during construction, soil contamination from spoil materials, and changes in water quality and flow regimes that could affect downstream aquatic habitats and biodiversity (World Bank, 2013). Furthermore, environmental assessments for hillside irrigation infrastructure have documented risks of surface drainage alteration and habitat degradation, including deterioration of water quality and soil erosion, if not properly mitigated (Environmental Impact Assessment Report for Gatsibo-8 site, 2013). These issues mirror broader landscape pressures in Rwanda, where high erosion risk due to steep topography and agricultural land use contributes to fertile soil loss and decreased ecosystem resilience (Bamurigire et al., 2020).

Mitigation measures typically include implementing soil control practices during construction, directing irrigation canals to downstream areas of dams, and using branching valleys near dam toes for controlled water distribution. Project EIA reports also recommend managing drainage systems and backfilling borrow pits to prevent water percolation and accumulation, as well as measures like replacing topsoil after construction to help restore fertility and minimize degradation (MINAGRI LWH EIA Report, 2024; Hakıruwızera et al.,2022). Other measures include introducing fish in reservoirs to control mosquito populations, measuring rainfall to monitor seepage, and enhancing safety through fencing, signage, and the deployment of security personnel. These interventions aim to balance the goals of agricultural productivity with environmental protection and public safety.

3.6 Institutional and policy frameworks

Institutional and policy frameworks provide the foundation for irrigation development in Rwanda. Key initiatives include the Rwanda Irrigation Master Plan and the Strategic Plan for the Transformation of Agriculture, which seek to expand irrigated areas, improve water efficiency, and strengthen climate resilience (Booth; Golooba Mutebi, 2014; Musabanganji et al., 2016). Despite these frameworks, the literature consistently identifies institutional challenges, including weak Water User Associations, inadequate technical supervision, and insufficient maintenance financing. These institutional gaps limit effective water allocation, reduce system performance, and constrain the socio-economic benefits of irrigation investments (Jones et al., 2022; Ngango; Hong, 2021). Although Integrated Water Resources Management principles are embedded in national policy, implementation at local and catchment levels remains uneven, highlighting governance constraints that undermine irrigation sustainability (Booth; Golooba-Mutebi, 2014; Diao et al., 2023).

3.7 Technological innovations

Technological innovations, including drip and sprinkler systems, solar-powered pumping, and digital tools for water scheduling and monitoring, provide tangible opportunities to improve irrigation efficiency and productivity. Studies show that integrating affordable and efficient irrigation technologies, such as drip irrigation, solar water pumps, and mobile-based controls, empowers smallholder farmers to conserve water, reduce labor and energy costs, and strengthen resilience against rainfall variability (Iradukunda et al., 2022). Pilot projects in Rwanda and similar contexts have demonstrated the potential of solar-powered irrigation to lower operational costs and increase productivity, while also reducing dependence on costly diesel pumps (Izar et al., 2021). However, adoption remains limited due to high upfront costs, insufficient technical support, and low awareness among farmers. Expanding access to these technologies, coupled with capacity-building programs, demonstration schemes, and supportive policy incentives, could significantly enhance the performance and sustainability of irrigation systems in Rwanda (Tesfaye et al., 2021).

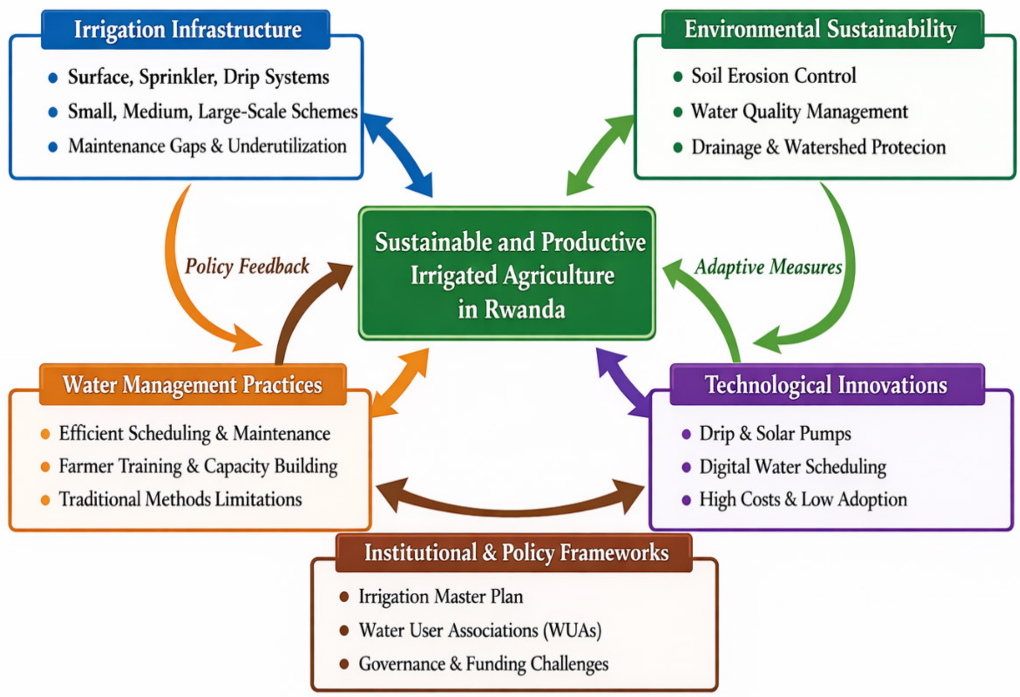

Figure 4. Key drivers, challenges, and strategies for sustainable irrigation in Rwanda. Source: Authors, 2025.

Table 2. Types and scale of irrigation systems in Rwanda.

Theme	Findings	Challenges	References
Water Management & Efficiency	49.7% irrigated plots use surface irrigation; 41% flood irrigation. Sediment accumulation, poor maintenance, and limited technical capacity reduce efficiency.	Low water productivity; inequitable allocation; smallholder vulnerability to drought.	FAO, 2017; World Bank, 2021; Mukanyandwi et al., 2018
Environmental Impacts	Soil erosion and altered drainage in marshlands & hillsides. Potential water quality decline in downstream habitats.	Necessitates integrated land–water planning; risk to ecosystem services.	World Bank, 2013; Bamurigire et al., 2020
Institutional & Policy Frameworks	Weak Water User Associations (WUAs); uneven implementation of IWRM. Limited technical supervision and maintenance financing.	Reduces system reliability; hinders equitable water allocation; limits socio-economic benefits of irrigation.	Booth; Golooba Mutebi, 2014; Jones et al., 2022; Diao et al., 2023
Technological Innovations	Drip and sprinkler adoption < 10%; solar pumps piloted in smallholder schemes. Digital water monitoring tools are emerging.	Potential for higher efficiency, reduced energy costs, improved climate resilience; adoption constrained by high cost & low technical capacity.	Iradukunda et al., 2022; Izar et al., 2021; Tesfaye et al., 2021

Source: Authors, 2025.

4. Discussion

The findings of this study indicate that Rwanda has made measurable progress in expanding irrigation infrastructure and introducing diverse irrigation technologies. However, only a small fraction of the nation's estimated irrigation potential is currently utilized, reflecting historical investment patterns, financing constraints, and operational inefficiencies (Mabhaudhi et al., 2025; Hakiruwizera et al., 2022). Traditional surface and flood irrigation remain dominant, particularly in marshlands and valley-bottom areas. While these systems are low-cost and feasible under gravity-fed conditions, they often result in significant water losses and lower efficiency compared to modern methods, limiting the full realization of productivity gains.

Adoption of advanced irrigation technologies, such as drip and sprinkler systems, remains limited due to high initial investment costs, complex maintenance requirements, and insufficient technical support. These barriers disproportionately affect smallholder farmers, who form the majority of irrigation users and are highly vulnerable to climatic variability (Ngango; Hong, 2021). The study further highlights that water management inefficiencies are compounded by institutional challenges, including weak Water User Associations (WUAs), limited technical supervision, and uneven implementation of Integrated Water Resources Management (IWRM) principles at local and catchment levels. Such governance gaps constrain effective coordination of irrigation operations, reduce system reliability, and hinder equitable water allocation.

Environmental consequences associated with irrigation development underscore the importance of integrated land–water management approaches. Hillside and marshland irrigation schemes can exacerbate soil erosion, alter drainage patterns, and impact water quality, particularly where mitigation measures are insufficient (World Bank, 2013; Bamurigire et al., 2020). Sustainable outcomes require consistent environmental monitoring, community engagement, and adherence to ecosystem-based irrigation planning (Mabhaudhi et al., 2025). Technological innovations, including solar-powered irrigation and digital water monitoring tools, present promising opportunities to enhance water use efficiency and system resilience. Evidence shows that renewable energy-driven systems can reduce reliance on diesel pumps, improve technical efficiency, and strengthen smallholder capacity to cope with rainfall variability (AllAfrica, 2025). Nevertheless, scaling these innovations necessitates supportive policy incentives, access to financing, and targeted capacity-building programs.

Overall, achieving sustainable irrigation in Rwanda will require coordinated interventions across technical, institutional, environmental, and policy domains. Balancing productivity improvements with environmental conservation and socioeconomic equity is essential to ensure that irrigation contributes meaningfully to food security, rural livelihoods, and climate resilience. By addressing infrastructural limitations, promoting the adoption of efficient technologies, strengthening governance mechanisms, and implementing robust environmental safeguards, Rwanda can advance toward a more productive and sustainable irrigated agriculture system.

5. Conclusions

This review highlights that Rwanda has made measurable progress in developing irrigation infrastructure and establishing supportive policies to enhance agricultural productivity and climate resilience. The country now hosts a range of irrigation schemes across marshlands, hillsides, and valley-bottom areas, supporting both smallholder and larger-scale agricultural operations. However, actual utilization of irrigation potential remains limited, and the dominance of traditional surface irrigation methods constrains water use efficiency, productivity, and environmental sustainability.

Operational challenges, including inadequate infrastructure maintenance, sedimentation, fragmented land holdings, and limited technical capacity, reduce the effectiveness of irrigation schemes. Small- and medium-scale farmers face particular constraints, while large-scale schemes disproportionately capture available resources, highlighting persistent inequalities in access to irrigation services. Environmental pressures, such as soil erosion, waterlogging, and altered hydrological regimes, further emphasize the need for careful planning and mitigation measures.

Modern irrigation technologies, including drip and sprinkler systems, solar-powered pumps, and digital water management tools, demonstrate clear potential to improve efficiency, reduce energy and labor costs, and enhance resilience to climate variability. Yet, their adoption remains constrained by high installation costs, limited technical support, and low awareness among farmers. Strengthening institutional arrangements, particularly Water User Associations, and integrating Integrated Water Resources Management (IWRM) principles at community and catchment levels, are critical to ensuring equitable water allocation, sustainable use, and system longevity.

Overall, achieving sustainable irrigated agriculture in Rwanda requires coordinated technical, institutional, and policy interventions. Key strategies include promoting modern and climate-smart irrigation technologies, enhancing farmer training and capacity building, reinforcing operation and maintenance practices, and adopting innovative solutions that balance productivity with environmental protection. Implementing these measures will improve water productivity, support rural livelihoods, and contribute to long-term food security and resilience under changing climate conditions.

6. Acknowledgments

The authors sincerely acknowledge all institutions that provided primary data for this study and those that made their data publicly available online. We are grateful to the Ministry of Agriculture and Animal Resources (MINAGRI), Rwanda Water and Forestry Authority (RWFA), National Institute of Statistics of Rwanda (NISR), and other relevant governmental and research institutions for their support. Special thanks also go to international organizations, including the Food and Agriculture Organization (FAO) and the Global Water Partnership (GWP), for providing access to valuable datasets and reports that informed this research. The contributions of these institutions were indispensable in enabling a comprehensive analysis of irrigation systems and water management in Rwanda.

7. Authors' Contributions

Sonia Ikundabayo: conceptualization; methodology; data curation; writing – original draft. *Jean de Dieu Bazimenyera:* formal analysis; validation; supervision; writing – review & editing. *Romuald Bagaragaza:* methodology; data analysis; validation; writing – review & editing. *Jean Bosco Ngarukiyimana:* formal analysis; interpretation; supervision; writing – review & editing.

8. Conflicts of Interest

The authors declare that they have no conflicts of interest relevant to this study.

9. Ethics Approval

Not applicable.

References

Ali, A., Hussain, T., & Zahid, A. (2025). Smart irrigation technologies and prospects for enhancing water use efficiency for sustainable agriculture. AgriEngineering, 7(4), 106.

AllAfrica. (2025). Rwandan farms go high-tech to fight drought. https://allafrica.com/stories/202509160204.html allAfrica.com

Bamurigire, P., Vodacek, A., Valko, A., & Rutabayiro Ngoga, S. (2020). Simulation of internet of things water management for efficient rice irrigation in Rwanda. *Agriculture*, 10(10), 431.

Bird, K., Chabé-Ferret, B., & Simons, A. (2022). Linking human capabilities with livelihood strategies to speed poverty reduction: Evidence from Rwanda. *World Development*, 151, 105728.

Bizimana, C., Usengumukiza, F., Kalisa, J., & Rwirahira, J. (2012). Trends in key agricultural and rural development indicators in Rwanda. *Rwanda Strateg Anal Knowl Support Syst SAKSS Minist Agric Anim Resour MINAGRI Kigali*.

Bizoza, A. R. (2021). Investigating the effectiveness of land use consolidation–a component of the crop intensification programme in Rwanda. *Journal of Rural Studies*, 87, 213-225.

Booth, D., & Golooba-Mutebi, F. (2014). Policy for agriculture and horticulture in Rwanda: A different political economy?. *Development Policy Review*, 32(s2), s173-s196.

Booth, D., & Golooba-Mutebi, F. (2014). Policy for agriculture and horticulture in Rwanda: A different political economy?. *Development Policy Review*, *32*(s2), s173-s196.

Celestin, H., Rukangantambara, H., & Pande, M. S. K. (2023). Performance Evaluation of Drip Irrigation System Under Onion Crop in Semi-Arid Region of Eastern Rwanda. *Performance Evaluation*, 41(2), 461-480.

CIFOR-ICRAF. (2020). Rwanda Irrigation Master Plan. Nairobi: CIFOR-ICRAF Knowledge Platform

Energy 4 Impact (2025)—Mercy Corps report on the solar irrigation market in Rwanda, including barriers and benefits.

Environmental Impact Assessment Report for Gatsibo-8 site. (2013). *Updated environmental impact assessment for hillsides irrigation infrastructure in Gatsibo-8*. Retrieved from https://www.scribd.com/document/483696174/updated-environmental-impact-assesment-for-hillsides-irrigation-infrastructure-in-gatsibo-8

Food and Agriculture Organization of the United Nations (FAO). (2017). *Irrigation in Africa in figures: AQUASTAT survey – 2016* (FAO Water Reports No. 43). FAO.

Food and Agriculture Organization of the United Nations (FAO). (2021). *Rwanda: Irrigation and drainage country profile*. FAO AQUASTAT Programme.

Food and Agriculture Organization of the United Nations (FAO). (2021). *FAO delivers Rulindo's first solar-powered irrigation system in Rwanda*. UN Rwanda. https://rwanda.un.org/en/110350-fao-delivers-rulindos-first-solar-powered-irrigation-system

Gaspard, N., Félicien, N., Noel, M. J. C., Claude, T. J., Claude, M. J., & Mburu, D. M. (2023). Impact of irrigation systems use in agriculture farming in Rwanda: a case study of kagitumba, nasho and Muyanza schemes.

Gebremedhin, T., Haile, G. G., Gebremicael, T. G., Libsekal, H., & Reda, K. W. (2023). Balancing crop water requirements through supplemental irrigation under rainfed agriculture in a semi-arid environment. *Heliyon*, 9(8).

Hakıruwızera, E., Topçu, E., & Uçar, Y. (2022). Water Resources and Irrigation in Rwanda. *Turkish Journal of Science and Engineering*, 4(1), 42-49.

Heinen, S. (2022). Rwanda's agricultural transformation revisited: Stagnating food production, systematic overestimation, and a flawed performance contract system. *The Journal of Development Studies*, *58*(10), 2044-2064.

Iradukunda, E., Kayibanda, V., & Ndagijimana, E. (2022, August). Use of solar powered auto irrigation system as solution of reduction of carbon dioxide (CO 2) emissions in Rwanda. *In*: 2022, IEEE PES/IAS PowerAfrica, 1-5. IEEE.

Izar-Tenorio, J. L., Jaramillo, P., & Williams, N. (2021). Techno-economic feasibility of small-scale pressurized irrigation in Ethiopia, Rwanda, and Uganda through an integrated modeling approach. *Environmental Research Letters*, 16(10), 104048.

Jones, M., Kondylis, F., Loeser, J., & Magruder, J. (2022). Factor market failures and the adoption of irrigation in Rwanda. *American Economic Review*, 112(7), 2316-2352.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., & Scardigno, A. (2014). Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agricultural Water Management*, 146, 84-94.

Lydie, M., & Lydie, M. (2022). Droughts and Floodings Implications in Agriculture Sector in Rwanda: Consequences of Global Warming. *The Nature, Causes, Effects and Mitigation of Climate Change on the Environment*. https://doi.org/10.5772/INTECHOPEN.98922

Mabhaudhi, T., Dirwai, T. L., Taguta, C., Kanda, E. K., Nhamo, L., & Cofie, O. (2025). Irrigation development and agricultural water management in Rwanda: A systematic review. In T. Mabhaudhi, V. G. P. Chimonyo, A. Senzanje, & P. P. Chivenge (Eds.), *Enhancing water and food security through improved agricultural water productivity: New knowledge, innovations and applications*, 361-384. Springer. https://doi.org/10.1007/978-981-96-1848-4_16

Mercy Corps / Energy 4 Impact (solar irrigation challenges and opportunities)
Energy 4 Impact. (2025). *Driving growth in Rwanda's solar irrigation market*. Mercy Corps / Energy 4 Impact. https://www.energy4impact.org/resources/rwanda-solar-irrigation-market-growth

Ministry of Agriculture and Animal Resources (MINAGRI). (2010). *Rwanda irrigation master plan (RIMP)*. Government of Rwanda.

Ministry of Agriculture and Animal Resources (MINAGRI). (2018). Strategic plan for the transformation of agriculture—Phase IV (PSTA 4), 2018-2024. Government of Rwanda.

Ministry of Agriculture and Animal Resources (MINAGRI). (2020). *National irrigation policy and strategy*. Government of Rwanda.

Ministry of Agriculture and Animal Resources (MINAGRI). (2024). *Environmental and Social Impact Assessment report for Giseke hillside site — LWH project*. Government of Rwanda. (EIA document, unpublished)

Mukanyandwi, V., Nahayo, L., Hakorimana, E., Gasirabo, A., & Otgon, S. (2018). Review on water resources management and key threats in Rwanda, East Africa. *Journal of Water Security*, *4*.

Musabanganji, E., Karangwa, A., & Lebailly, P. (2016). Intensification of smallholder agriculture in Rwanda: scenarios and challenges towards a sustainable transformation. In *5th African Association of Agricultural Economists (AAAE) conference" Transforming smallholder agriculture in Africa: The role of policy and governance"*.

National Institute of Statistics of Rwanda (NISR). (2021). *Seasonal Agricultural Survey 2021: Annual report*. Government of Rwanda.

National Institute of Statistics of Rwanda (NISR). (2023). Seasonal agricultural survey: Season A 2023 report. Government of Rwanda.

Ngango, J., & Hong, S. (2021). Adoption of small-scale irrigation technologies and its impact on land productivity: Evidence from Rwanda. *Journal of Integrative Agriculture,* 20(8), 2302-2312. https://doi.org/10.1016/S2095-3119(20)63417-7

Nzeyimana, I. (2021). Farmer-Led irrigation development in Rwanda.

Perez-Guzman, K., Imanirareba, D., Jones, S. K., Neubauer, R., Niyitanga, F., & Naramabuye, F. X. (2023). Sustainability implications of Rwanda's Vision 2050 long-term development strategy. *Sustainability Science*, 18(1), 485-499.

Rengasamy, P. (2018). Irrigation Water Quality and Soil Structural Stability: A Perspective with Some New Insights. *Agronomy*, 8(5), 72. https://doi.org/10.3390/AGRONOMY8050072

Research Letters article (modern irrigation technologies and smallholders) Recent Developments in Water-Smart Irrigation Technologies for Smallholder Farmers. (2024). *Journal of e-Science Letters*, 16(1). https://scienceletters.researchfloor.org/recent-developments-in-water-smart-irrigation-technologies-for-smallholder-farmers

Rwanda Agriculture and Animal Resources Development Board (RAB). (2020). *Rwanda irrigation master plan*. Government of Rwanda.

Rwanda Water Resources Board (RWB). (2022). The state of soil erosion control in Rwanda, 2022. Government of Rwanda.

Rwanda Water Resources Board (RWB). (n.d.). Rwanda water portal: National water resources and irrigation potential. Government of Rwanda. https://waterportal.rwb.rw

Smith, P., Gregory, P. J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., & Bellarby, J. (2010). Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554), 2941-2957. https://doi.org/10.1098/RSTB.2010.0127

Tesfaye, M. Z., Balana, B. B., & Bizimana, J. C. (2021). Assessment of smallholder farmers' demand for and adoption constraints to small-scale irrigation technologies: Evidence from Ethiopia. *Agricultural Water Management*, 250, 106855.

Tuyisabe, J. B., Silungwe, F. R., & Mahoo, H. F. (2024). Assessment of physical status of the irrigation structures in Nyarubogo irrigation scheme, Rwanda. *African Journal of Empirical Research*, 5(4), 1561-1575. https://doi.org/10.51867/AJERNET.5.4.130

World Bank. (2013). Safeguard policy issues: Land Husbandry, Water Harvesting, and Hillside Irrigation Project. World Bank Group.

World Bank. (2021). Rwanda agricultural transformation and irrigation development: Opportunities and challenges for sustainable water management. World Bank Group.

Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Copyrights