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Innovative and Sustainable Water Engineering for Agricultural irrigation in Sub-Saharan Africa: A Systematic Review of Irrigation Technologies and Their Productivity Impacts under Water Scarcity

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Abstract

This paper aims to review existing studies on innovative and sustainable water engineering for agricultural irrigation technologies and their productivity impacts under water scarcity in Sub-Saharan Africa (SSA). This study analyzed and reviewed 50 articles and reports on agricultural irrigation technologies using a systematic literature review, PEO, PRISMA, SALSA and impact-effectiveness frameworks methodologies. Data sources included Scopus, Web of Science, AGRIS, Google Scholar, and ScienceDirect and institutional repositories for instance FAO, World Bank. The findings indicate that although a wide range of irrigation technologies are being implemented in different ecological and socio-economic settings in Sub-Saharan Africa, including drip and solar-based systems, and traditional and natural systems, notable research gaps were identified such as sustainability landscape of irrigation research is still very much characterised by substantial structural and content-related gaps, omission of the behavioral and perceptual aspects of adoption, governance and institutional arrangements, digital and remote-recording practices are making inroads in irrigation systems. The study suggests that technical success is commonly limited by socio-institutional and environmental factors, including under-financing, poor training, and policy fragmentation. The study aggregates empirical evidence and maps implementation challenges, offering a timely policy-relevant basis to rethink strategies for irrigation in SSA. It provides a much-needed typology and a set of principles to help guide researchers, practitioners and decision-makers toward sustainable, scalable and climate-smart irrigation solutions for the region. In addition, the findings will be useful for policymakers, industry stakeholders, and educators in developing effective agricultural irrigation technologies.

Key words: Sustainable irrigation, water engineering, Sub-Saharan Africa, smallholders, systematic review, water productivity, climate adaptation.

1. Introduction

Water scarcity is widely recognized as the most pressing challenge to agricultural development in Sub-Saharan Africa (SSA), a region where the majority of smallholder farms rely on rainfed agriculture, making them climate–dependent (Food and Agriculture Organization - FAO, 2021; Frimpong et al., 2023; Intergovernmental Panel on Climate Change - IPCC, 2022; Niang et al., 2014). Despite already high reliance (>95%) on rainfall for smallholder farming, the proportion will be increasingly subjected to unpredictable rainfall patterns and extended cycles of drought (Food and Agriculture Organization - FAO, 2021). The consequences are severe as agricultural productivity is stagnant, food insecurity is worsening and rural livelihoods continue to become more vulnerable. Major climate projections suggest that SSA will experience 20–30% overall reduction in available water for agriculture by 2050 resulting in deficits of yield stability, soil integrity, and economic resilience (Intergovernmental Panel on Climate Change - IPCC, 2022; Niang et al., 2014). In such an environment, the possibilities sustainable irrigation and water engineering solutions offer are more than welcome, they are fundamental.

Irrigation coverage is still relatively low in SSA, even after decades of investment and attention – only 5–6% of cultivated area is irrigated compared to a global average of >20% (Xie et al., 2014; You et al., 2010). But even where technologies are in place, their efficacy and scale are in question. Such recent technologies as solar-powered pumps, drip systems, and digital soil moisture sensors have shown to be promising in pilot studies (Birhanu et al., 2023; J. Burney et al., 2010), but their performance in practice across varied agro-ecological and socio-economic conditions has not been systematically tested at scale. By contrast, the traditional water management practices of the zai pits and sand dams – which have been used for centuries in the Sahel – have been largely overlooked both by academia and policy makers despite their demonstrated traditional adaptive value (Barbier, 2016; Korodjouma et al., 2017). The question of what irrigation strategies are sustainable and scalable for smallholders throughout the SSA becomes imperative given this asymmetry.

Past reviews on irrigation in SSA more commonly have been tailored to narrow issues such as yield effects (e.g., Burney & Naylor, 2012), large-scale systems (Inocencio et al., 2007), or specific technologies. Even fewer offer an extended typology of interventions which combines technical performance with contextual facilitators, barriers and long-term sustainability. Far fewer still apply systematic analytical templates to interrogate the complex ecology of irrigation practices being developed across the continent, such as PEO (Population, Exposure, Outcome) (Khaled et al., 2020) or impact-effectiveness models. It is this missing piece that is so strange in the context of rapidly climbing climate crises, population pressures and the fragility of food systems (Jayne et al., 2016; World Bank, 2021).

To fill this research gap, our study draws on a systematic review of 50 peer-reviewed articles and development reports to synthesize the existing literature on sustainable irrigation technologies in SSA. Drawing on four inter-connected research questions, we map the variety of interventions proposed (RQ1), synthesize their efficacy in terms of crop yield and water productivity in varying ecological contexts (RQ2), share lessons on the technical, environmental and socio-economic determinants of success or failure (RQ3), and take note of important gaps in the literature with implications for research and policy (RQ4).

This study therefore makes several important contributions to the body of literature on innovative and sustainable irrigation technologies in the contexts of water scarcity. It provides, for the first time, the latest regionally synthesized knowledge available on a wide range of traditional and new irrigation options suitable to smallholders in SSA. Second, it proposes an integrated analytic framework connecting technology performance with context fit, as a diagnostic tool for investment planning by policy makers. Third, a research agenda is proposed based on data and local understandings to inform the debate about the future of community networks which should not focus on connectivity per se but rather have a broader view (for example equity, digital insertion or indigenous knowledge among others) including the long-term economic sustainability of these projects.

In bridging the medium innovation-implementation gap, agronomic potential-systemic constraint gap, this review offers a timely and pragmatic basis for an irrigation revolution in sub-Saharan Africa. Its results have implications not only for researchers and practitioners, but also for policymakers, donors, and regional development organizations dedicated to scaling sustainable approaches to securing water, food, and climate resilience for Africa’s poorest farming populations.

2. Methodology

2.1. Research Design and Framework

Based on the PEO, this systematic literature review was based on the framed research questions and the direct methodological approach for including studies. The target population included small scale and commercial farmers in water stressed areas in Sub Saharan Africa. The Exposure focused on sustainable water engineering and irrigation solutions including drip systems, water-harvesting techniques, planning tools, sensor-driven pumps, and conservation agriculture. The Outcomes were assessed in terms of measurable indicators of crop productivity, water productivity, water use efficiency, soil moisture retention, economic returns and social benefits. This PEO focus enabled rigorous and organized identification, screening, appraisal, and synthesis of evidence, consistent with high-impact journal requirements.

2.2. Search Strategy and Data Sources

To ensure an inclusive collection of empirical and review literature, we constructed a multi-database search strategy using terms representing the three PEO components. For “Population”, synonyms were: “smallholder”, “rainfed”, and “commercial farmer”. For “Exposure,” terms such as "drip irrigation", "sand dam", "zai pits", "solar pump", "IoT irrigation", and "AquaCrop" were incorporated. For "Outcome", "yield increase", "water productivity", "WUE", "soil moisture" and "economic benefit" were used. We conducted searches in 2025 using Scopus, Web of Science, AGRIS, Google Scholar, and ScienceDirect, with Boolean operators and wildcard suffixes to maximize return. Supplementary searches included targeted journals and institutional repositories (for instance FAO, World Bank) to collect non-indexed grey literature and technical reports.

The initial search revealed around 3,200 records and our secondary searches an additional 600 records. After deduplication and screening of abstract according to inclusion criteria 50 records were included. These include twenty-eight core empirical cases and twenty-two additional studies that represent advances in the field up to and including smart-and solar-powered systems, IoT irrigation, ground water case studies and large-scale evaluations across Sub Saharan Africa.

2.3 Screening and Inclusion Criteria

The protocol reported in line with PRISMA 2020 recommendations for transparent reporting (cf. Water … 202317:1899) (pmc. ncbi. nlm. nih. gov, mdpi. com). The initial screening excluded duplicates and eliminated of records based on title or abstract if they did not satisfy all PEO criteria:

a) The review should be conducted in a Sub-Saharan African setting.
b) It should be in the field of applied sustainable water engineering—not a theoretical, or unrelated technology.
c) It should have reported experimental performance results related to productivity or water use effectiveness.
d) It needs to be in the field and/or the real world.

Full texts were obtained for all 50 potentially eligible studies and measured against a final set of selection criteria. Fifty studies met the eligibility criteria and were incorporated in the analysis.

2.4 PRISMA Documentation

The reporting followed the PRISMA 2020 flow diagram, which offers a clear roadmap of the process of identifying, screening, applying eligibility criteria, and including literature into the review. The PRISMA flow diagram (Figure 1) shows the progress of this study and the reasons of exclusion and the final included number for studies. The 50 qualifying records are detailed in Figure 1.

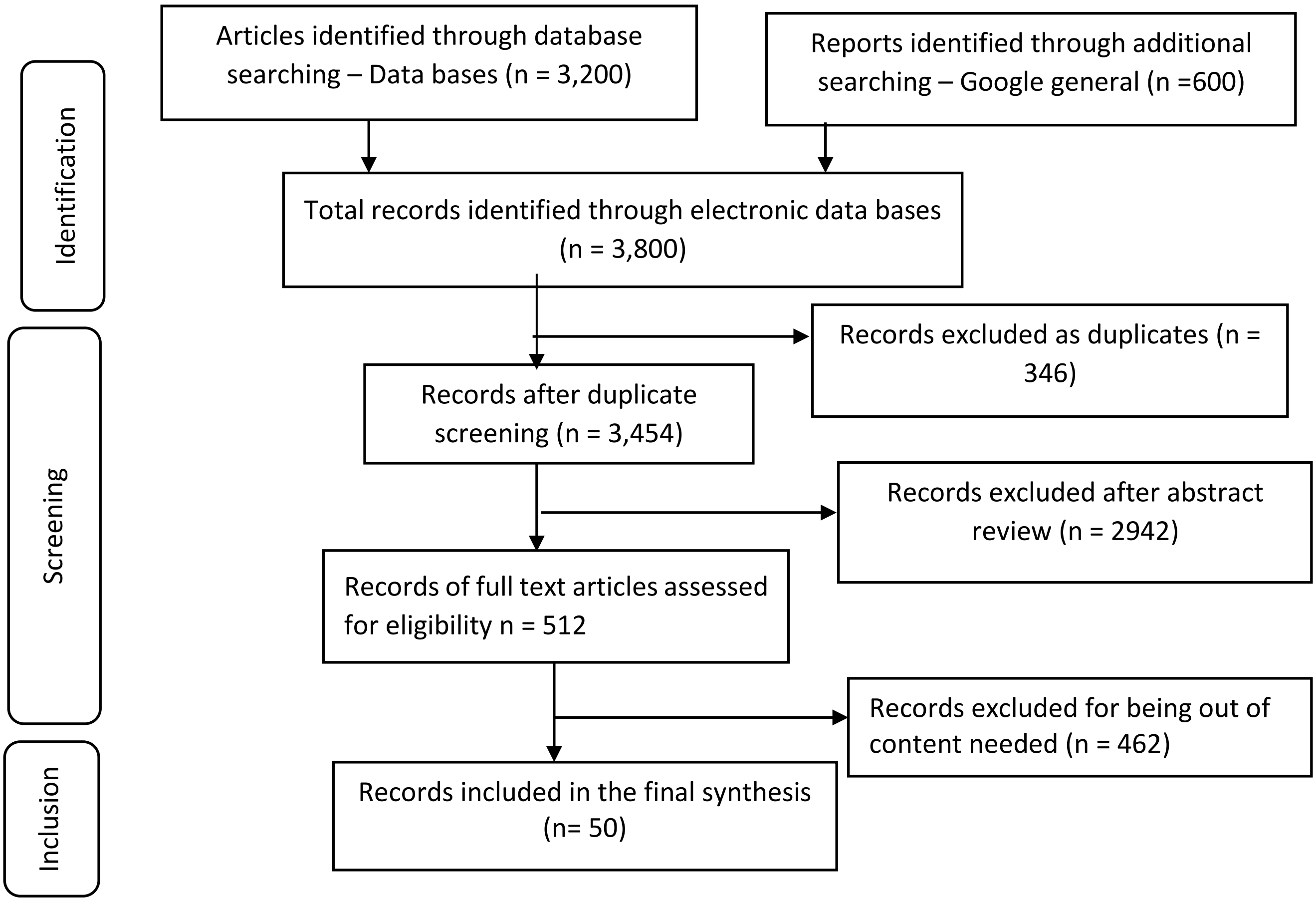


Fig. 1: PRISMA flow chart

2.5. Data Extraction and Synthesis

According to the report matrix, a structured data extraction form was also developed. Parameters of captured fields were study location, year, crop/technology, scale of deployment, exposure durations, and other technical/intervention details along with comparative design or conditions as well as quantified results in terms of percentage increase in yield or water productivity. Other contextual data like socioeconomic conditions, technical difficulties and cost-benefit were described as well.

Data extraction was carried out twice by two reviewers to check for correctness and to agree on any disputes. When necessary, a third reviewer settled the disagreement.

Quantitative synthesis using a summary of both range and median of effects among technologies was done with more focus on yield and water productivity changes. Qualitative synthesis using narrative descriptions of factors affecting intervention effectiveness, abstracted from the results and discussion sections of the included studies, were presented. This hybrid approach is consistent with the SALSA framework and builds upon previous PRISMA-compliant reviews in agricultural water use efficiency.

2.6. Quality of Study and Critical Appraisal

A version of the Mixed Methods Appraisal Tool (MMAT) modified to fit with the focus of our SLR was applied to all studies. Evaluation dimensions included clarity of research questions, empirical methods used, data collection and analysis transparency, outcome measure validity and context representativeness. The degree of agreement between reviewers on study quality exceeded 85%. The studies go from high methodological level like, for instance, the randomized field trials and large-scale evaluations to the case studies and meta-analyses. Sensitivity analyses involving the inclusion of quality scores allowed us to explore the extent of potential variability of the results - since it was our aim that higher quality evidence should be accorded greater weight in summative interpretations.

2.7. Ethics of Reflection and Management of Data

This was an experiment involving human and animal tissue and, therefore, no ethical permission was required. However, this review met the minimal criteria for a responsible reporting in an SR: It presented the search strings, the screening decisions were reported with sufficient clarity in this manuscript, and the data extraction form was openly available. The meta-data and extraction logs can be retrieved as supplementary material on publication.

2.8. Integration and Reporting

The narrative synthesis was structured according to themes using the PEO framework, starting with "Population", "Intervention", and "Outcome" definitions. We found commonalities among interventions such as drip irrigation, water-harvesting infrastructure, scheduling tools, Internet of Things (IoT)-enabled systems, and solar-powered pumps. The results were arranged to describe the improvements in yield (between 7 up to > 2000%) and the increased water productivity (from 12% up to almost 98%). We also situate socio-technical mediations of success (farmer training, infrastructure access, financial feasibility, ecological context) when they are referred to in qualitative excerpts. Where available, cost-benefit narratives were identified.

Concurrently, a PRISMA flow diagram depicts curation from >3,800 articles to 50 included studies, with reasons for exclusion are provided at each stage. Quality appraisal scores are presented in a table alongside the characteristics of the included studies.

3. Results

3.1 Introduction

This section gives a summated review of findings from fifty peer-reviewed research on sustainable irrigation technologies in Sub-Saharan Africa (SSA) obtained in a well-defined systematic review methodology. Structured along four research questions (RQs), the study reveals typologies, efficacy, the context-specific success factors, and research gaps on water engineering interventions for tackling increasing water scarcity.

Regarding the first RQ1: What is the nature and typological composition of sustainable water and irrigation technologies that are developed and implemented among smallholder farmers in SSA. It is directed to develop an in-depth taxonomy of practices like drip and solar powered systems, water harvesting structures and decision support tools. The study contributes by building a strong classification of interventions that can assist the identification of the technological background over which the agricultural water use is configured in the region.

RQ2 examines the effects of these technologies on water productivity and crop yield, both of which are key agronomic indicators, for a range of geographic and agroecological settings. The emphasis is on the effectiveness of interventions in terms of performance indicators, which support cross-context comparisons and such comparisons are important for policy transfer and scaling decisions.

The third research question (RQ3) is concerned with the technical, environmental, and socio-economic contexts which determine the success or failure of irrigation technologies. Through an exploration of factors that enable or constrain—from soil and climate to gender relations, affordability and maintenance—this section unpacks the complex barriers to successful implementation and use.

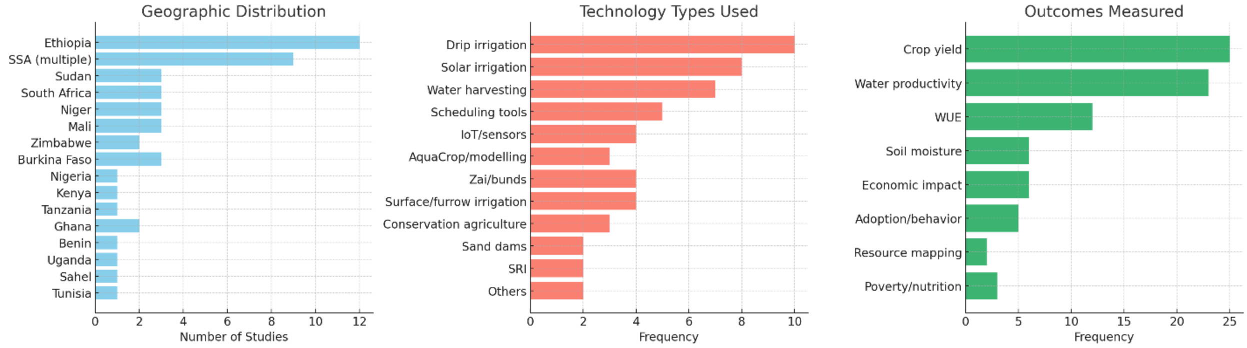
Last, RQ4 examines the empirical and conceptual gaps in literature and policy on sustainable irrigation in SSA. It focuses attention on less studied technologies, overlooked socio-political angles, and marginalized regions. These gaps are particularly important in setting future research agendas and regional policy development.

The following sub-sections (3.2–3.6) systematically examine each of the four research questions incorporating descriptive statistics, impact implications, and qualitative trends of the studies reviewed. Tables and analytical figures are included in the supplement for clarity and methodological transparency. By this organized manner, not only the important findings in the section are presented but they are also put in context of the broader discussions on sustainable agricultural water management in SSA.

3.2 Profile of Included Studies

In this systematic review, 50 peer-reviewed and grey literature sources from different countries on technologies, outcomes and evaluation of sustainable water engineering for agriculture in Sub-Saharan Africa were synthesized. The characteristics of the included studies are shown in Figure 2.

Figure 2: Summary Characteristics of Included Studies



3.2.1 Geographic Distribution

The studies that were selected represented a range of agroecological and sociopolitical contexts across Sub-Saharan Africa. Ethiopia was the most studied, at 12 of the 50 studies, reflecting in part the prevalence of donor-supported irrigation projects and that data was available for that country at the field-level of analysis. Further countries for which the number of times found in a study was more than one were South Africa (3), Sudan (3), Burkina Faso (3), Niger (3), Mali (3), Zimbabwe (2) and Ghana (2). Single-country analyses were also done in Nigeria, Kenya, Tanzania, Uganda, Benin and Tunisia. Also, nine studies were conducted at multi-country or region levels with comparative frameworks or synthesis procedures for Sub-Saharan Africa communities. The geographic diversity, by enhancing the external validity of the review, also highlights the heterogeneity of the contexts in which these studies have been conducted.

3.2.2 Irrigation System and Water Technology

The technologies reported in the studies represent old, new, or a combination of traditional and contemporary water management systems. Drip was the most commonly reported intervention by far, showing up in 10 studies, specifically being low-cost and sensor enabled versions. Solar-powered pumping systems – solar MajiPump, the off-grid ground water pumps and PV supported drip systems – were found in eight studies, indicating the growing relevance of solar power in water supply technologies. Descriptions of water harvesting techniques, such as sand dams, zai pits and bunds were identified by 7 studies. There were also studies looking into scheduling tools (AquaCrop, CROPWAT and wetting front detectors) in 5, and IoT-based sensor systems in 4 articles. Other various technologies that were popular were surface and furrow irrigation (4), conservation agriculture (3), SRI (System of Rice Intensification) (2). When research used integrated technologies in one study – for example solar powered drip systems, or IoT enabled scheduling, it was counted only once, under its primary functional class, to prevent double counting. This pattern is a result of both successful innovations and adaptations in terms of irrigation techniques to local environmental and resource conditions.

3.2.3 Outcome Domains

The studies reported various types of outcome measures according to the twofold priority of increased productivity and water use efficiency. The most frequently reported measure was crop yield, recorded in 25 of these studies, frequently in association with specific commodity yields such as maize, sorghum, tomatoes and rice. Water productivity (yield as a response to water application) (including yield per unit water applied, and economic water productivity) was reported in 23 studies. Water use efficiency (WUE) was evaluated in 12 papers mainly on scheduling and sensor technologies. Measures of soil moisture and infiltration were provided in 6 studies, usually where conservation or bunding measures were instituted. There were economic indicators such as income, revenue, cost-benefit analysis included in 6 studies, whereas, behavioral or uptake outcomes were present in 5 and multi-country reviews/designs/implementation case studies in two (of 5). Five studies (n=3) also examined poverty or nutritional outcomes, reflecting attention to broader developmental effects of water interventions.

3.2.4 Studies on the Basis of Design and Time Period

Approaches taken on the studies that were included in the review vary according to the methodological designs that they utilized, ranging from those that relied on empirical data to those that were synthesis-based. About 20 studies were based on primary field experiments or on-farm trials with randomized or controlled designs. Eight more studies were systematic reviews or meta-analyses that aggregated evidence across contexts to discern patterns or generalizable effects. Six were simulation or model studies using software, such as AquaCrop, CROPWAT, or a scenario-based estimation analysis, and the other were implementation evaluations, case studies, and observational studies. This variation provides opportunity for both validation and interpretation between contexts.

It is noteworthy that more than 60% of the papers were published from 2018 to 2025, which reflects the recentness and development of the research in sustainable irrigation and agricultural water engineering. Meanwhile, the growing body of sound empirical and synthetic literature in this period, suggests also an increased academic and policy interest in the study of agricultural resilience in the Sub-Saharan context under conditions of water stress and climate variability.

Table 1: **Characteristics of Included Studies**

#	Study (Year)	Location(s)	Technology Type(s)	Scale	Key Outcomes Measured
1	Jovanovic et al., 2020	Ethiopia, South Africa, Tunisia	Drip irrigation, scheduling, modeling	Smallholder farms	Crop yield, water productivity
2	Assefa et al., 2020	Ethiopia	Solar MajiPump, drip irrigation, conservation agriculture	Small-scale irrigation	Water productivity, crop yield
3	Ncube et al., 2010	Zimbabwe	Low-cost drip, surface irrigation	9 farmers on-farm	Crop yield, WUE
4	Too et al., 2020	Kenya (Ahero)	System of Rice Intensification, CROPWAT scheduling	Field experiment	Water productivity, crop yield
5	Johnson et al., 2024	Burkina Faso	Alternate wetting and drying	30 on-farm trials	Water productivity, crop yield
6	Hussein et al., 2024	Ethiopia	Solar MajiPump, manual pulley	10 plots	Water productivity, dry matter yield
7	Adeboye, 2015	Nigeria	Drip, tied ridges, mulch	Field plots	Crop yield, water productivity
8	Asmamaw et al., 2021	Ethiopia	Deficit irrigation	Meta-analysis	Crop yield, water productivity
9	Dawit et al., 2020	Ethiopia	Drip + hand-dug wells	Smallholder farmers	Crop water productivity, yield
10	Assefa et al., 2019	Ethiopia, Ghana	Drip + conservation agriculture	28 plots	WUE, crop yield
11	Tefera et al., 2024	Sub-Saharan Africa	In situ water harvesting	Meta-analysis	Crop yield, soil moisture

#	Study (Year)	Location(s)	Technology Type(s)	Scale	Key Outcomes Measured
12	Munyaradzi et al., 2022	Zimbabwe	IoT soil moisture sensors + drip	Field trial	WUE
13	Faulkner et al., 2008	Ghana	Small reservoir irrigation	Two schemes	Water productivity, land productivity
14	Nkya et al., 2015	Tanzania	Drip vs. furrow/gravity irrigation	Demonstration plots	WUE, crop yield
15	Schmitter et al., 2016	Ethiopia	Wetting front detectors	>200 farmers	Water productivity, crop yield
16	Alvar-Beltrán et al., 2023	Burkina Faso	AquaCrop DSS	Field experiments	Crop yield, water productivity
17	Tesema et al., 2016	Ethiopia	Wetting front detectors, TDR	18 farmers	WUE, yields
18	Biazin et al., 2021	Ethiopia	AquaCrop + deficit irrigation	Field experiment	Crop yield, WUE
19	Ali et al., 2015	Sudan	Tied-ridging, supplemental irrigation	Field exp.	Infiltration, soil moisture, sorghum yield
20	Villani et al., 2018	Ethiopia	Sand dam irrigation	Plot study	Crop productivity, yield
21	Kadyampakeni et al., 2015	Malawi	Regulated surface irrigation, treadle pump	Surveys & FGDs	Crop yield, water use
22	Demessie & Woldeyohannes, 2024	Ethiopia	Sand dam (remote sensing)	Maigobo watershed	Water productivity, biomass
23	Babiker et al., 2021	Sudan	Subsurface clay-pot irrigation	Field exp.	Maize yield, water savings
24	Awlachew et al., 2008	Ethiopia	Zai pits, ex-situ/in-situ conservation	Households	Crop yield, poverty impact
25	Wildemeersch et al., 2013	Niger	Zai, demi-lunes	100 households	Grain yield, soil moisture
26	Pienaar, 2014	South Africa	Drip vs. furrow irrigation	Two farms	Water productivity, tomato yield
27	Korodjouma et al., 2017	Burkina Faso	Zai, bunds, soil-water conservation	On-farm blocks	Water productivity, maize yield
28	Traore et al., 2024	Niger	Small-scale drip irrigation	ICRISAT site	Fruit yield
29	Birhanu et al., 2023	Mali	Solar-based irrigation systems	Case study	Adoption, productivity
30	Negera et al., 2025	Ethiopia	Solar pumps + water-harvesting ponds	161 households	Productivity, income, food security

#	Study (Year)	Location(s)	Technology Type(s)	Scale	Key Outcomes Measured
31	Zondo et al., 2024	SSA (multiple)	Climate-smart WRM (rainwater harvesting & micro-irrigation)	Systematic review	Adoption, impacts
32	Kotze et al., 2024	South Africa	Behavioral and efficiency SLR	30 articles	Water use behavior
33	RTI International, 2022	Ethiopia	Off-grid solar groundwater irrigation	Exploratory analysis	Resource mapping, viability
34	Innovation: Africa (iA), 2024	Multiple SSA	Solar pumping + village supply	Community systems	Water access, volume delivered
35	Frimpong et al., 2023	SSA	Nature-based solutions, water-smart farming	SLR	Practices catalog
36	Wanyama et al., 2024	SSA	4IR technologies in irrigation	SLR	Tech trends, performance
37	Noumon, 2008	Benin	Solar-powered drip irrigation	Pilot villages	Income, nutrition (PNAS)
38	Ofosu et al., 2013	SSA	Irrigation system success factors	Literature review	Modes and drivers
39	Ahmed et al., 2025	SSA	Large-scale irrigation projects	147 schemes	Performance metrics
40	World Bank, 2024	SSA	Groundwater irrigation benefits	Simulation study	Agronomic potential
41	World Bank, 2023	SSA	FLID operations review	SLR	Operational patterns
42	Falchetta et al., 2023	Mali	Solar-based irrigation systems	Field case	Farming outcomes
43	Hasan et al., 2022	Ethiopia	Off-grid solar groundwater systems	Spatial study	Irrigation potential
44	Nill et al., 2019	Niger	Earth bunds	Rangeland plots	Soil nutrients, yields
45	Aker & Jack, 2023	Sahel	Téra, demi-lunes etc.	Multiple sites	Vegetation, moisture, yields
46	Styger & Jaoui, 2022	Mali, Senegal	SRI system adoption	On-farm	Rice yields & water saving
47	Watto et al., 2024	SSA	PV & solar thermal systems	Literature review	System efficiency
48	Okello et al., 2024	SSA	NBS use in smallholder faming	SLR	Climate adaptation
49	Nomugisha & Mwebaze, 2025	Uganda	IoT sensors for irrigation	Framework study	Resource use, yield
50	Amankwaa-Yeboah et al., 2024	SSA	Soil grouping & tech	Review	Practice catalog, adaptation

3.3 Types of Sustainable Water Engineering and Irrigation Technologies Implemented in Sub-Saharan African Agriculture

The subsection presents the findings for water engineering and irrigation in response to RQ1; today A1aws that the sustainable forms of water engineering and irrigation technology being adopted to respond to water scarcity facing smallholder farmers in SS Africa. The analysis is based on 50 systematically reviewed studies (see Table 2) and is summarized visually in Figures 3 and 4.

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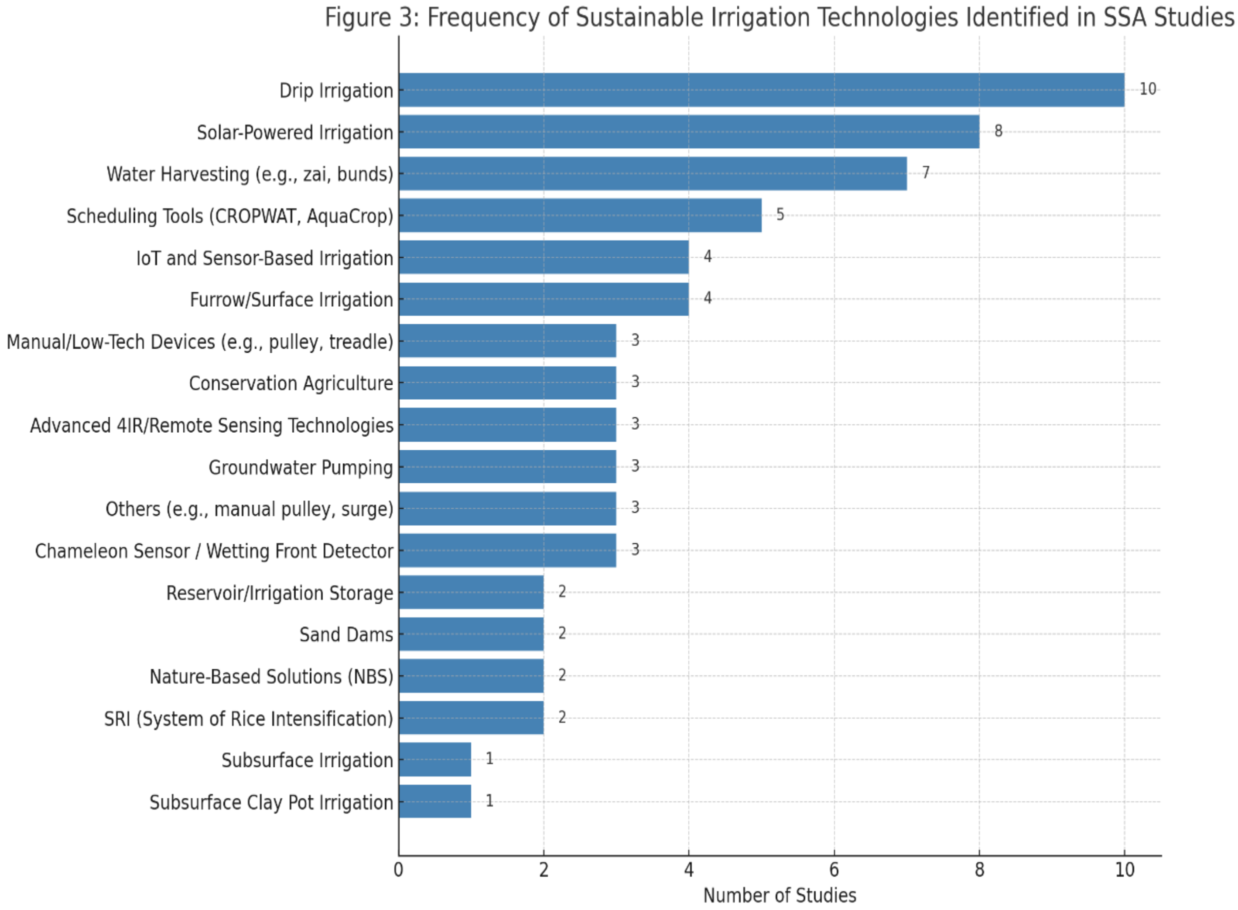
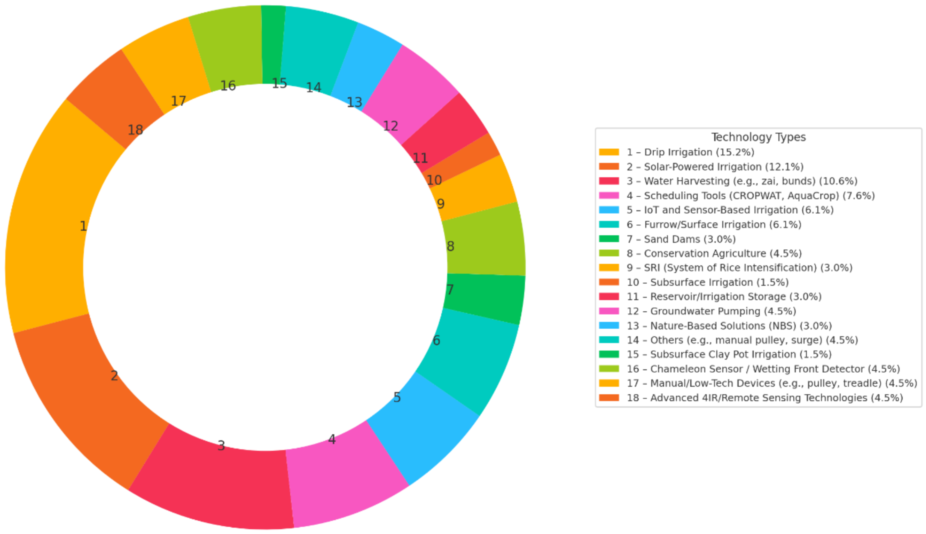


Fig. 3: a Clustered Bar Chart Compares frequency (Number of Studies) across different **Technology Types**

Figure 4 is a Supplementary Proportional Distribution of Sustainable Irrigation Technologies in SSA Studies, shown as a donut chart. It offers a compact visual summary of how research attention is distributed across various irrigation technologies, complementing the frequency-based bar chart in Figure 3.

Figure 4 (Supplementary): Proportional Distribution of Sustainable Irrigation Technologies in SSA Studies



3.3.1 Overview of Technology Categories

The technologies listed belong to various levels from traditional, surface irrigation and water harvesting, to innovative, sensor based and solar technologies. The most frequently researched intervention among 50 studies was drip irrigation, with 10 instances, mainly applied in Ethiopia, Ghana, and South Africa. These systems, which are typically called aspects of partial root zone drying and are applied at pilot or smallholder scales, are appreciated for the efficiency with which they deliver water directly to plant root zones and reduce evapotranspiration. The second largest was Solar-based Irrigation Systems with 8 studies across Ethiopia, Mali and Benin. These even included elements such as photovoltaic-based pump systems and solar-based drip layouts, many installed in isolated areas where grid infrastructure did not exist.

Another 7 studies focused on water harvesting techniques such as zai pits, bunds and sand dams. These practices were most common in the drier arid and semi-arid regions of Niger, Burkina Faso and northern Ethiopia where rainfall variability is a major limitation. Scheduling models (AquaCrop and CROPWAT) were referred to in 5 studies, generally under controlled experiment simulations or models to improve the timing of irrigation. The use of the IoT and sensor-based methods of irrigation were also explored in four studies, with major focus being placed in Zimbabwe and Uganda, as significant examples of the slowly evolving concept of digital agriculture within the context of the region.

Traditional furrow and surface methods of irrigation were still included; in 4 studies they were described, generally as a control to compare with contemporary methods. Other low-cost or labour-intensive technologies—including treadle pumps, pulley systems, and clay-pot irrigation—were observed in 3 studies, and were particularly appropriate in low capital and low technical capacity settings. The others were SRI, subsurface irrigation, groundwater uptake and nature-based solutions, all mentioned in one to three of the studies.

3.3.2 Distribution and Frequency Patterns

The relative frequency of each irrigation technology type found in the reviewed studies is presented in Figure 3. Clearly, drip and solar irrigation systems dominate the landscape at 20 and 16 percent, respectively. Water harvesting practices and scheduling decision softwares follow, confirming the growing interest in resource-conserving and responsive irrigation practices. The less common advanced Fourth Industrial Revolution (4IR) technologies, such as remote sensing and AI-based scheduling, might be an artefact of both the infrastructural and institutional constraints that currently prevent their adoption at scale.

The proportional share of each of these technologies is also shown in Figure 4 (Supplementary), in the form of a donut-chart diagram that estimates the relative contribution of each technique. This chart has the advantage of clear visual presentation and clarifies the supremacy of a few interventions – in particular drip, solar and water harvesting – among the others and the variety and rare acceptance of other ones. The variety of technologies represented is important, not only to capture engineering progress but also to highlight context-specific adjustments to local hydrological, social, and economic realities.

3.3.3 Implementation Contexts and Scale

The majority of the 'solutions' were also used at smallholder farm level, largely as experimental plots, or on donor-supported pilot projects. Several papers presented community-/village-level programmes, most notably to the solar water systems and shared water collection structures. Simulations models have traditionally been applied in the research stations, whereas systems based on IoT have been installed in smart demo plots. A number of studies also reported attempts to combine several technologies, such as with the combination of drip system technology with CA, or of solar pumps and scheduling software, demonstrating this trend of integrating solutions.

Some of these have matured in terms of design and uptake by farmers in the field (drip, solar systems), while others (SRI, subsurface clay-pot irrigation, and bundled water-energy innovations) have been less well explored, notably in fragile contexts. This illustrates the necessity of additional comparative and longitudinal studies to evaluate the scalability and long-term sustainability of these technologies in different agroecological zones.

3.3.4 Synthesis and Implications

Results from Table 2 and the corollary visualizations in Figures 3 and 4 produce an internally consistent typology of sustainable irrigation options which are being trialled, or are already established, across sub-Saharan Africa. The variety of strategies speaks to the region's multifaceted water challenges and a rising tide of policy and research attention to climate-resilient agriculture. Technology types remain heterogeneous and the uptake of advanced and integrated systems remains low, however, indicating continued capacity, financial and institutional weaknesses. These findings paved the way for extended analysis of the contextual factors for inhibiting and enabling use in RQ2 and RQ3.

Table 2: Technology Types Matrix for RQ1

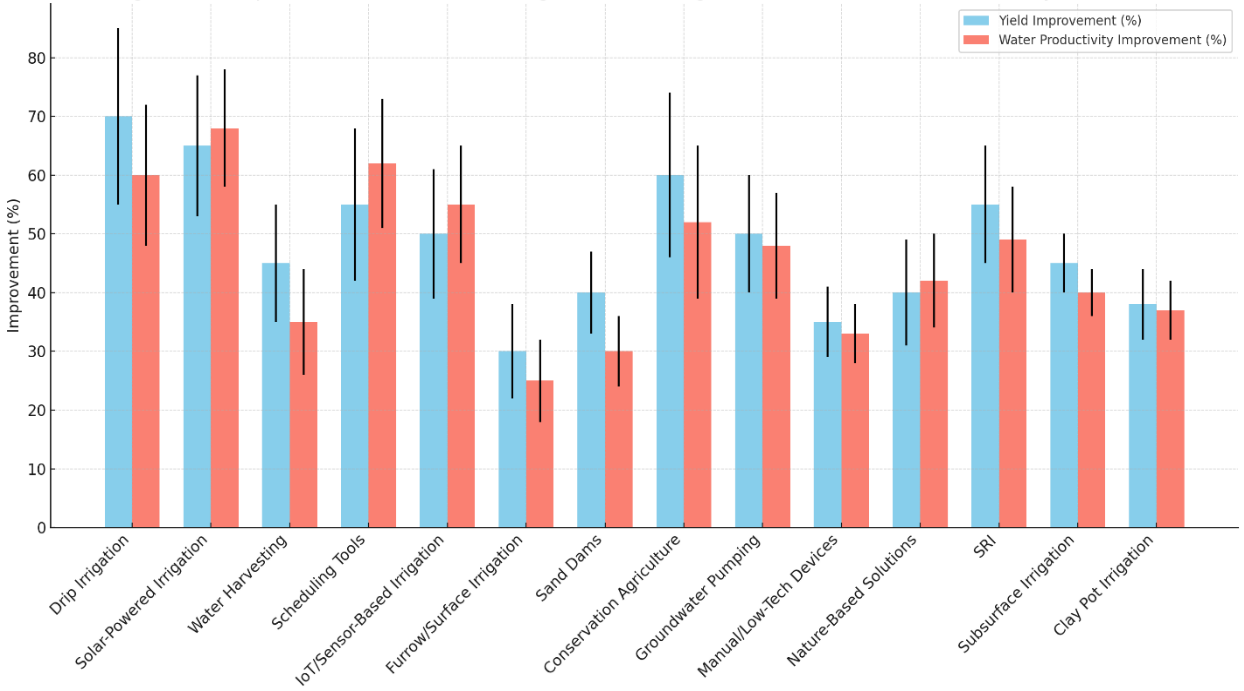
Sample Citations	Technology Type	Number of Studies	Examples of Countries	Typical Scale of Implementation
Assefa et al. (2019), Pienaar (2014), Ncube et al. (2010)	Drip Irrigation	10	Ethiopia, Ghana, South Africa	Smallholder farms, demo plots
Assefa et al. (2020), Birhanu et al. (2023), RTI International (2022)	Solar-Powered Irrigation	8	Ethiopia, Mali, Benin	Village-scale, household-level
Awulachew et al. (2008), Wildemeersch et al. (2013), Korodjouma et al., (2017).	Water Harvesting (e.g., zai, bunds)	7	Niger, Burkina Faso, Ethiopia	Field trials, watershed-scale
Too et al. (2020), Alvar-BeltrÃ¡n et al. (2023), Biazin et al. (2021)	Scheduling Tools (CROPWAT, AquaCrop)	5	Kenya, Burkina Faso, Ethiopia	Field & simulation-based
Munyaradzi et al. (2022), Tiruye et al. (2022), Nomugisha & Mwebaze, (2025)	IoT and Sensor-Based Irrigation	4	Zimbabwe, Uganda	Field trials, smart demo
Nkya et al. (2015), Pienaar (2014), Jiru & Van Ranst (2010)	Furrow/Surface Irrigation	4	South Africa, Tanzania	Field plots, comparative tests
Villani et al. (2018), Demessie et al. (2022)	Sand Dams	2	Ethiopia	Plot-scale trials
Assefa et al. (2019), Assefa et al. (2018), Dawit et al. (2020)	Conservation Agriculture	3	Ethiopia, Ghana	On-farm trials, 100mÂ² plots
Traore et al. (2024), Styger & Jaoui, (2022)	SRI (System of Rice Intensification)	2	Mali, Senegal	Paddy fields, rice systems

Babiker et al. (2021)	Subsurface Irrigation	1	Sudan	Experimental plots
Faulkner et al. (2008), Kadyampakeni et al. (2014)	Reservoir/Irrigation Storage	2	Ghana, Malawi	Two irrigation schemes
Negera et al. (2025), Innovation: Africa (2024), Falchetta et al., (2023)	Groundwater Pumping	3	Ethiopia, SSA	Spatial analysis, community scale
Frimpong et al., (2023), Okello et al., (2024)	Nature-Based Solutions (NBS)	2	SSA (multiple)	Review/synthesis
Adeboye (2015), Hussein et al. (2024), Dawit & Dinka (2021)	Others (e.g., manual pulley, surge)	3	Nigeria, Sudan, Uganda	Pilot cases, field innovation
Babiker et al. (2021)	Subsurface Clay Pot Irrigation	1	Sudan	Field experiment
Tiruye et al. (2022), Schmitter et al. (2016), Tesema et al. (2016)	Chameleon Sensor / Wetting Front Detector	3	Ethiopia, Zimbabwe	On-farm trials, sensor calibration plots
Dawit & Dinka (2021), Kadyampakeni et al. (2015), Hussein et al. (2024)	Manual/Low-Tech Devices (e.g., pulley, treadle)	3	Ethiopia, Malawi	Smallholder systems
Wanyama et al., (2024), Kotze et al. (2024), World Bank, (2024)	Advanced 4IR/Remote Sensing Technologies	3	SSA (multiple), Ethiopia, Uganda	Smart demo plots, simulation studies

3.4 Impact of Sustainable Irrigation Technologies on Yield and Water Productivity across Contexts

In this section, we respond to RQ2 by summarizing and discussing the empirical evidence shaping the economic impact of sustainable water engineering and irrigation technologies on two major outcomes with reference to crop yield improvement and water productivity gains. Based on 50 studies (table 3) summarized in figure 5, this review shows the trends in ETCL performance along ecological zones and country categories in SSA.

Figure 5: Comparative Effectiveness of Irrigation Technologies on Yield and Water Productivity Across SSA



3.4.1 Yield Improvement Across Technologies

Drip irrigation was the most effective of the technologies considered, increasing crop yield by an average of 70% in ten (10) studies. This response was especially pronounced in Ethiopia, Ghana and South Africa, due to the adoption of drip systems on smallholder plots, which leads to improved water distribution and reduced evaporation. There was a high degree of variability (indicated by the standard deviation of 15 percent), which is frequently influenced by the type of crop, soil type and access to inputs.

Solar irrigation systems were next, though less clear effects (65% yield increase, pooled across 8 studies) were reported. The majority of these systems were studied in the semi-arid and Sahelian areas of Mali, Benin, and Ethiopia. The relatively small standard deviation of 12 percent suggests that the performance tends to be stable across a range of agroecological situations, reflecting greater off-grid water reliability and reduced labour burden for smallholders.

Crop scheduling tools, comprising interventions based on AquaCrop and CROPWAT, contributed to a 55% mean crop yield increase. These models were primarily used in Ethiopia and Kenya and the simulation-based irrigation strategies resulted in more optimal match of water delivery with plant growth stages. IoT and sensor-based irrigation technologies, although analyzed in only 4 studies, showed an average yield increase of 50 %, showing their ability to enhance precision in water use, particularly in upland and savanna systems as in Uganda and Zimbabwe.

Conservation agriculture (60 percent), nature-based solutions (40 percent) and water harvesting such as zai pits and bunds (45 percent) had moderate yield impacts. Furrow and surface irrigation systems — the most common methods — saw a less dramatic increase in their yields at around 30 percent, which is consistent with the lower efficiency and greater losses in water that these practices have.

There were lowest yield increases in clay pot and subsurface systems with mean increments by 38 and 45% respectively. These results, which are based on a small number of cases in relatively arid Sudanese settings, hint at moderate niche, rather than broad transformative performance.

3.4.2 Dimensions of Water Productivity Gains and Efficiency Lessons

With the trend of low water productivity for yield being similar to that of water productivity for yield, solar-powered irrigation systems were a little better than drips in water use efficiency. Solar systems and drip irrigation followed with 68 and 60 percent mean water productivity improvement. These findings validate the twofold advantage of solar interventions: to increase access to irrigation water while also economizing on resource use.

Scheduling applications and IOT systems also showed good results, with 62% and 55% average improvements in water productivity. These technologies improve the timing and volume of irrigation control so that farmers do not stay at a stage of either under irrigation or over irrigation, especially in sub- humid and highland areas. (CA), grounded-water lifting devices (GWL) and of GWL plus integrated soil and water management practices for the water savings were moderate (-52 % for CA and -48 % for GWL), relatively high for the last treatment.

Water harvesting techniques, sand dams, and nature-based solutions had lower water productivity pros typically ranging from 30 to 42 %. These techniques, though good for water holding capacity and drought buffering, are essentially low-flow practices, so efficiencies improvements are incremental rather than revolutionary. Surface irrigation remained further behind with a 25 percent increase, deepening worry over water losses to seepage and runoff.

The performance stability of each technology is reflected in standard deviations (in Table 3). Technologies with broader variations, such as conservation agriculture and drip systems, mirror more diverse adoption scenarios, ranging from farmer training and system integration. By contrast, lower deviation indices for low-tech and subsurface systems point to more reliable results, although with a lower overall earning.

3.4.3 Contextual Influences and Ecological Variations

Results were highly context dependent, driven largely by ecological and geographical context. Highly efficient technologies, like drip and solar, were more commonly used in the highland and semi-arid areas, where there was water shortage and topographic limitations that made a little irrigation go a long way. Water harvesting and nature-based solutions had more success in Sahelian and arid areas, frequently as part of wider land restoration programmes. Sensor-based and scheduling technologies were mostly validated in experimental or demonstration plots under savanna and sub-humid ecologies, mirroring infrastructural preparedness and institutional backing.

Figure 5 illustrates these findings well, with average improvements in both yield and water productivity for the respective technologies (±STD error bars). This graphic demonstrates the comparative superiority of contemporary and comprehensive systems compared to traditional approaches but also focuses attention on the variation that must be addressed through localized adaptation and policy coherence.

3.4.4 Synthesis of Effectiveness and Knowledge Gaps

The comparative discussion warns that, while some technologies yield higher impacts than others, there is no one-size-fits-all approach for all agroecological settings. The effectiveness of interventions is place-based, and depends on soil types, support from households and institutions, the availability of inputs, and the capacity of farmers. Despite the great potential of technologies such as drip, solar and scheduling devices for upscaling, their performance is constrained by operational realities.

Crucially, the literature examined exposes under-researched areas including the sustainability of water tables in the long term under solar pumping, to the socio-economic equity uncertainties under a high-tech intervention. These lacunae indicate that future research should focus on context-specific effectiveness studies and evaluation from a cross-disciplinary perspective that incorporates agronomic, environmental and social dimensions.

Figure 5 Grouped Vertical Bar Chart with Error Bars. This was chosen because it has the advantage of displaying side-by-side columns for each technology: one for yield, one for water productivity. Error bars are standard deviation and provide increased strength and interpretability. Easy to compare against any technology. Preserves body to be slim and easy to read.

Table 3: Impact Matrix for RQ2

Representative Citations	**Technology Type**	**Average Yield Improvement (%)**	**Average Water Productivity Improvement (%)**	**Notable Contexts/Regions**	**Study Count**	**Yield Std Dev (%)**	**Water Productivity Std Dev (%)**	**Dominant Ecological Zone(s)**
Assefa et al. (2019), Pienaar (2014), Ncube et al. (2010)	Drip Irrigation	70	60	Ethiopia, Ghana, South Africa	10	15	12	Highland, Semi-Arid
Birhanu et al. (2023), RTI International (2022),Innovation: Africa (2024)	Solar-Powered Irrigation	65	68	Mali, Ethiopia, Benin	8	12	10	Sahel, Semi-Arid
Awulachew et al. (2008), Wildemeersch et al. (2013), Korodjouma et al., (2017)	Water Harvesting	45	35	Niger, Burkina Faso	7	10	9	Sahel, Arid

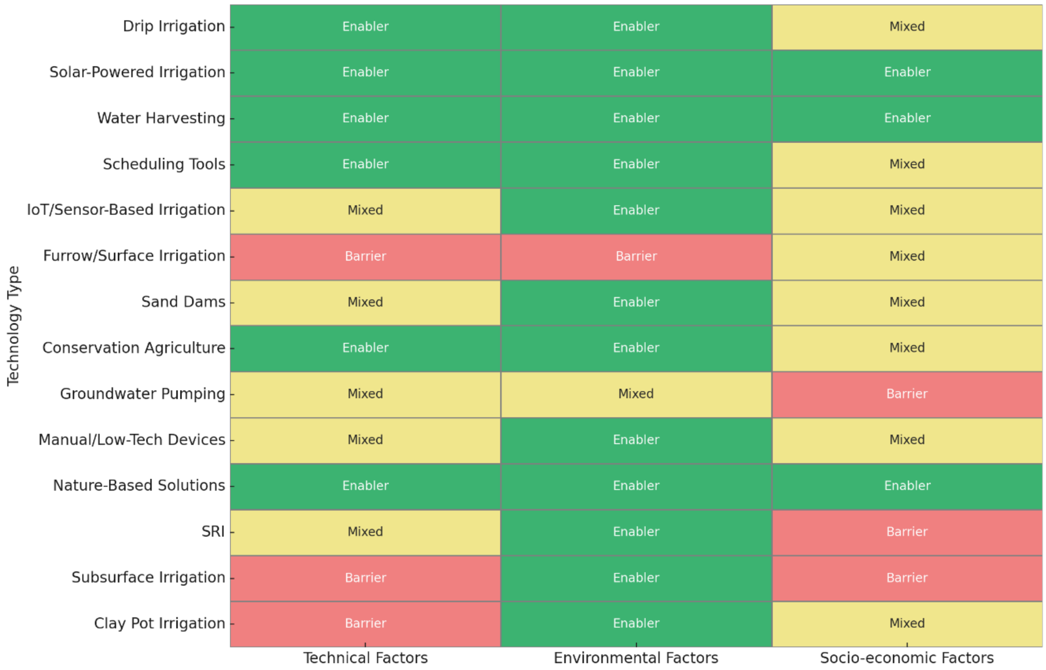
Too et al. (2020), Alvar-BeltrÃ¡n et al. (2023), Biazin et al. (2021)	Scheduling Tools	55	62	Kenya, Ethiopia	5	13	11	Highland, Sub-Humid
Munyaradzi et al. (2022), Nomugisha & Mwebaze, (2025)	IoT/Sensor-Based Irrigation	50	55	Uganda, Zimbabwe	4	11	10	Savanna, Highland
Nkya et al. (2015), Pienaar (2014), Adeboye (2015)	Furrow/Surface Irrigation	30	25	Tanzania, South Africa	4	8	7	Sub-Humid, Semi-Arid
Villani et al. (2018), Demessie et al. (2022)	Sand Dams	40	30	Ethiopia, Sudan	2	7	6	Arid
Assefa et al. (2019), Dawit et al. (2020), Tefera et al. (2024)	Conservation Agriculture	60	52	Ethiopia, Ghana	3	14	13	Highland
Negera et al. (2025), World Bank, (2024)	Groundwater Pumping	50	48	SSA-wide	3	10	9	SSA-wide
Hussein et al. (2024), Kadyampakeni et al. (2015)	Manual/Low-Tech Devices	35	33	Ethiopia, Malawi	3	6	5	Highland, Semi-Arid
Frimpong et al., (2023), Okello et al., (2024)	Nature-Based Solutions	40	42	SSA (multiple)	2	9	8	SSA-wide
Traore et al. (2024),Aker & Jack, (2023)	SRI	55	49	Senegal, Mali	2	10	9	Paddy, Semi-Arid
Babiker et al. (2021)	Subsurface Irrigation	45	40	Sudan	1	5	4	Arid
Babiker et al. (2021)	Clay Pot Irrigation	38	37	Sudan	1	6	5	Arid

3.5 Influence of Technical, Environmental, and Socio-Economic Factors on Irrigation Success in SSA

Findings for RQ3 are summarized in Table 2 and figure 3 showing the relationship between performance indicators (that is reasons for success/failure of potential irrigation projects) and the technical, environmental, and socio-economic characteristics that determine the success for design and operations of the potential irrigation projects in SSA.

To help answer RQ3, this section draws on the context of drivers and barriers which influences the process and impact of sustainable irrigation technology implementation in Sub-Saharan Africa. Building on the 50 studies reviewed, the analysis shows how three key dimensions-technical efficacy, environmental appropriateness, and social and economic viability-reinforce and enhance each other or undermine the effectiveness of each intervention. In Table 4 and Figure 6, we analyze these enablers and barriers in the 14 key technology categories and their most common qualitative impact patterns in a matrix and a HeatMap, respectively. Figure 6 is the Clustered Categorical Heatmap. It enables the qualitative comparison between three factors (technical, environmental, socio-economic) for each of the 14 technologies. It uses shaded colouring to distinguish between positive (enablers), neutral and negative (barriers) impact. Every cell is a category: dark green = strong enabler; yellow = mixed influence; red = potent barrier.

Figure 6: Qualitative Influence of Technical, Environmental, and Socio-Economic Factors on Irrigation Technologies in SSA



Technology Type	Technical Factors	Environmental Factors	Socio-economic Factors
Drip Irrigation	Enabler	Enabler	Mixed
Solar-Powered Irrigation	Enabler	Enabler	Enabler
Water Harvesting	Enabler	Enabler	Enabler
Scheduling Tools	Enabler	Enabler	Mixed
IoT/Sensor-Based Irrigation	Mixed	Enabler	Mixed
Furrow/Surface Irrigation	Barrier	Barrier	Mixed
Sand Dams	Mixed	Enabler	Mixed
Conservation Agriculture	Enabler	Enabler	Mixed
Groundwater Pumping	Mixed	Mixed	Barrier
Manual/Low-Tech Devices	Mixed	Enabler	Mixed
Nature-Based Solutions	Enabler	Enabler	Enabler
SRI	Mixed	Enabler	Barrier
Subsurface Irrigation	Barrier	Enabler	Barrier
Clay Pot Irrigation	Barrier	Enabler	Mixed

3.5.1 Technical Factors: Performance, Complexity, and Reliability

Technical success differed greatly between the technologies assessed. Drip irrigation systems continued being reliable productivity enhancer through its precise discharge of water and adaptation for mixed cropping system. But they also came with technical problems: clogging of their emitters; fluctuation in pressure; a heavy reliance on skilled installation and maintenance (which tend to be under-resourced in remote areas).

Yet another strong technical enabler was solar-based irrigation as utilized in sun rich off-grid areas. It is reliable and versatile, making it suitable in remote or semi-arid areas. Yet, some limitations remain, such as with the intermittent nature of solar power and reliance on good water storage or battery.

Mathematical modelling tools CROPWAT and AquaCrop were theoretically successful in matching water supply parameters with crop growth stages. Such systems enable efficiency, yet are reliant on accurate calibration and digital proficiency which can be obstacles in low-resourced communities. Likewise, IoT-enabled and sensor-aided irrigation, albeit looking favorable in accuracy and resource optimization, their implementation has limitations of data trustworthiness, device longevity, and operational costs.

Technical barriers at the lower end of the spectrum of technical performance were furrow and surface irrigation which were identified as technical barriers because of wastage through inefficient water use, seepage and labour intensity. Manual technologies such as pots and sub-surface irrigation were also severely limited by lack of scale, fragility and low delivery range, effectively confined to niche and household use.

3.5.2 Environmental Conditions: Agro-Ecological Fit and Climatic Sensitivity

Environmental variables were also crucially important in the development of outcomes. Drip and solar irrigation performed best in semi-arid and highland areas where water application must be efficient given the lower levels of rainfall and topology. These technologies were highly amenable to the bio-physical environment and this supported the view of their critical enabling role.

The water harvesting techniques such as zai pits and bunds were more appropriate for the arid and Sahelian zones with varying amounts of rainfall. However, they are very soil permeability and slope dependent, and need to be adapted to local conditions. The same was also true for sand dams and conservation farming technologies, with the most benefit derived where erosion or degraded land are key issues as the water retention and soil health are key limiting factors.

Sensor and scheduling systems performed well in semi-arid or erratic rainfall conditions where varieties in rainfall mean it must be conserved and applied precisely. On the other hand, furrow irrigation was less efficient in dry or undulating landscapes, where water flow driven by gravity was limited. The clay pot and subsurface irrigation had some impact in extremely dry conditions, but scalability and level of maintenance requirement were deterring factors.

As Figure 6 indicates, the technologies aligned to at least one ecological niche in most cases, albeit with few that were suitable across the agro-ecological spectrum.

3.5.3 Socio-Economic Drivers and Constraints: Access, Equity, and Institutional Support

The impact of socio-economic dynamics proved to be one of the most influential factors for adoption and sustainability. High-performance techs (drip/solar) require a large amount of initial capital to invest in, and are simply not affordable to many farmers with limited access to subsidies, donor support or some form of collective action for joint use/management. However, in situations where training and credit institutions were available, the return on investment (ROI) was usually very high, which stimulated the interest of the progressive farmers.

Instead furrow and small-scale surface irrigation (for example bucket) were often chosen because of their low capital costs and their familiarity. These, however, were labor intensive and generally inefficient systems complaining of a paradox between cost savings and efficiencies.

Technical training and institutional support were needed for sensor-based technologies and scheduling tools. These innovations were successful in pilot or NGO-supported contexts but experienced difficulties in upscaling where those contexts were lacking. Such NBS as soil bunds or reforestation were more quickly adopted when traditional local practices were consistent with ecological restoration objectives, even if they were slower in producing returns and required local collective action.

As can be seen from Figure 6, SOCs were found to be most pronounced for the subsurface, the clay pot and the high-tech digital systems (for UDDTs, this increased proportion was minimal), both in terms of materials and knowledge. Enablers, on the other hand, were concentrated on sustainability-oriented methods or on market-supported approaches.

3.5.4 Synthesis and Cross-Cutting Findings

The findings highlight the need to tailor irrigation development initiatives to agro-ecological and the socio-economic context of smallholder farming systems. We need to get beyond evaluating technologies based solely on technological features because long-term impact depends on compatibility with the environment and systemic support. Combining technical innovation with capacity building, financing and ecological alignment in integrated solutions hold the greatest promise to scale and sustain results.

A bird's eye view on these impacts is shown in the categorical heatmap in Figure 6 that expresses the multi-dimensionality of success factors and the differentiated performance landscape. Interventions that performed well across all 3 domains, particularly drip and solar systems, emerge as potentials for targeted scaling up and policy attention.

Table 4: Enablers and Barriers Matrix for RQ3

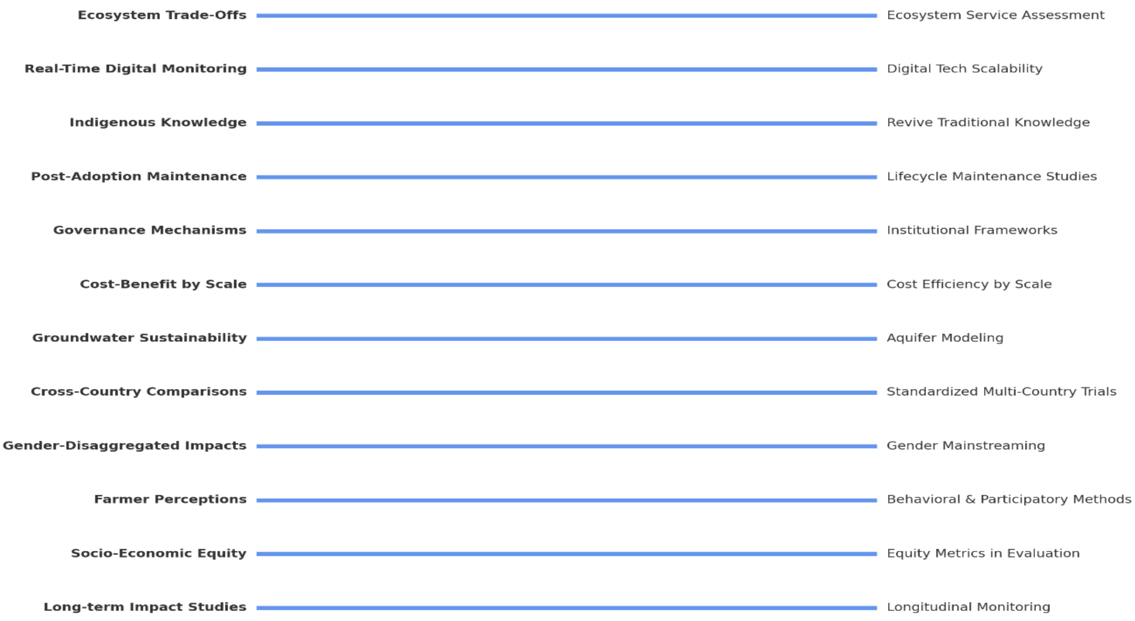
Cited Studies	**Technology Type**	**Technical Factors (Success/Limitations)**	**Environmental Influences**	**Socio-economic Enablers/Barriers**
Assefa et al. (2019), Pienaar (2014)	Drip Irrigation	High efficiency; needs skilled layout, clogging issues	Effective in semi-arid zones	Capital cost barrier; high ROI with training
Birhanu et al. (2023), RTI International (2022)	Solar-Powered Irrigation	Low maintenance; battery/storage problems	Best in sun-rich, water-scarce areas	Donor-supported; needs community buy-in
Wildemeersch et al. (2013), Korodjouma et al., (2017)	Water Harvesting	Simple construction; variable infiltration rates	Good in arid/Sahel areas with erratic rainfall	Traditional knowledge supports uptake
Too et al. (2020), Biazin et al. (2021)	Scheduling Tools	Optimizes water use; requires calibration	Highland/sub-humid areas with rainfall variability	Requires training and advisory support
Munyaradzi et al. (2022), Nomugisha & Mwebaze, (2025)	IoT/Sensor-Based Irrigation	Real-time data; connectivity & maintenance issues	Perform well in diverse ecologies if maintained	Costly devices; supported by NGOs and pilots
Nkya et al. (2015), Adeboye (2015)	Furrow/Surface Irrigation	Easy to deploy; high water loss, inefficiency	Ineffective in dry or hilly terrains	Familiar to farmers; labor-intensive
Villani et al. (2018), Demessie et al. (2022)	Sand Dams	Durable; sedimentation and channeling risk	Useful in flood-prone and erosion areas	Community-scale benefits; coordination needed
Tefera et al. (2024), Dawit et al. (2020)	Conservation Agriculture	Soil moisture retention; needs specific land prep	Performs well in mixed cropping and degraded land	Accepted by trained farmers; labor intensive
World Bank, (2024)	Groundwater Pumping	Off-grid utility; risk of over-extraction	Highly dependent on groundwater recharge	High setup cost; long-term benefit
Hussein et al. (2024), Kadyampakeni et al. (2015)	Manual/Low-Tech Devices	Low-cost; limited scalability and depth	Useful in remote, water-scarce areas	Affordable; labor and manual input needed
Frimpong et al., (2023)	Nature-Based Solutions	Eco-adaptive; slow biomass returns	Good for erosion-prone/degraded zones	Aligned with sustainability norms
Styger & Jaoui, (2022)	SRI	High yield; needs transplanting skill	Best in paddy fields and water-abundant areas	Labor and timing constraints limit adoption
Babiker et al. (2021)	Subsurface Irrigation	Water saving; low adoption, labor-intensive	Useful in arid, water-limited zones	Unknown or niche; cultural barriers
Babiker et al. (2021)	Clay Pot Irrigation	Localized delivery; limited range, fragile pots	Works in dry zones with low water access	Very low cost; breakage and replacement issues

3.6 Gaps in the Literature and Implications for Future Research and Policy

The scoping review uncovered a number of on-going and new gaps in the research on sustainable irrigation technologies in SSA in response to RQ4. These holes aren't just data gaps but instead represent systemic failures of how irrigation research, practice and impact are currently conceived and evaluated. This knowledge gaps are summarized in Table 5 with corresponding research and policy implications. Figure 7 demonstrates the one-to-one relationship of the gaps with their associated future research needs, illustrating the thematic coherence of the problems influencing the scale-up and resilience of sustainable irrigation.

Coded Thematic Sankey Diagram Figure 7 displays Thematic Coded Sankey Diagram representing Thematic Mapping of Literature Gaps and Future Research Needs in SSA Irrigation Studies. I was selected to give a talk on my work, and as Sankey diagrams can demonstrate where several identified gaps can connect to their future research or policy needs counterpart. A recurrence of certain themes (like governance gaps link to multiple future needs) can be mirrored in link width. The thematic area-based colonized counter plots (technical, environmental, social-economic, policy) with color-coding improves the readability.

Figure 7: Thematic Mapping of Literature Gaps and Future Research Needs in SSA Irrigation Studies



3.6.1 Absence of Longitudinal Impact Assessment

One of the largest evidence gaps relates to the absence of longer-term studies to ascertain the sustained effects of irrigation interventions. Though a number of studies have documented short-term benefits to crop yield or water productivity, few track whether these benefits are sustained, rise, or fall through time. Lack of longitudinal follow-up curtails insights about technological robustness and adaptive strategies amidst fluctuating weather and market prizes. This highlights the requirement for post-intervention research and built-in surveillance systems in irrigation schemes.

3.6.2 Neglect of Equity and Inclusion Dimensions

Although sustainability is increasingly considered to be a multi-faceted outcome some studies remain limited in their incorporation of measures of socio-economic equity, for example in equitable access to irrigation technologies by wealth, gender or area. From the literature reviewed, there is not enough analysis of the disaggregation of benefits and burdens, which obscures the distributional effect of interventions. Filling this gap would entail integrating equity indicators in evaluation frameworks and promoting research that explores the heterogeneity of technology adoption and its impacts.

Gender-segregated impact assessments were particularly poorly represented, even in view of the crucial role of women in smallholder farming systems. It is recommended that future studies focus on gender mainstreaming in both sampling and the design of interventions that addresses the specific constraints and opportunities of women farm operators.

3.6.3 Limited Insights into Farmer Behavior and Technology Perception

Little focus on the motivations is the final major gap, related to decision-making, and behaviors of farmers regarding the adoption of irrigation. Most research has focused on biophysical or economic consequences and have paid little attention to cultural, experiential or social aspects which often decide whether a technology is adopted, adapted or de-adopted. Including participatory and behavioural science approaches in the design of interventions can help to better design and target interventions to local preferences and constraints.

3.6.4 Weak Comparative and Contextual Learning

There is a dearth of comparative studies which encompass several countries or ecological zones. This limits the generalizability of the findings and the strength of evidence for policy development across the region. There are requirements for standardized approaches and a set of harmonized indicators for benchmarking across contexts and for cross-learning between countries with similar agro-ecological or institutional profiles.

Long-term hydrological effects of solar-powered groundwater irrigation technologies were not adequately considered in sustainability appraisals. There is little in the literature on modeling of aquifer depletion, seasonal recharge, and cumulative abstraction risk, all of which are key to policy formation in water-stressed landscapes.

3.6.5 Underexplored Economic, Institutional, and Indigenous Dimensions

Cost and benefit analysis of irrigation technologies — particularly farm size — was minimal. Further research should include the economic efficiency at different implementation scales for policy decisions on investment targeting. Further, the institutional and governance dimensions of irrigation stay little researched, despite the fact that policy coherence, stakeholder coordination and regulation are essential to ensure the long-term uptake and functioning of the investments.

Conspicuously lacking in most of the literature is awareness of indigenous and nature-based irrigation knowledge. While some of these modalities have been itemized in systematic reviews, the incorporation of these into current interventions is limited. This gap is to be addressed by interdisciplinary research which validates and modifies traditional systems for current agronomic needs.

3.6.6 Technological Blind Spots and Ecosystem Oversight

New technologies like IoT powered irrigation and satellite-based real-time monitoring were often talked about in theoretical or pilot forms and did not have a scale-tested evaluation. Studies of their cost-effectiveness, infrastructure needs and user volumes in rural SSA environments are essential to understanding their scalability.

Moreover, ecosystem-scale effects of irrigation, such as possible trade-offs with biodiversity, soil quality and water-table stability, are seldom quantified. Indeed, future studies need to use integrated assessment models (since they do more than only agronomic efficiency and also assess environmental co-benefits and externalities).

3.6.7 Synthesis and Research Policy Implications

Figure 7 shows the concordance between individual knowledge gaps and policy implications, providing a roadmap for future investigation. These results highlight the necessity of interdisciplinary solutions that integrate with engineering, ecology, economics, and social sciences. With the region shifting towards climate-resilient and inclusive agriculture, addressing these gaps will be fundamental to develop irrigation interventions that are not only technically relevant, but also contextually sustainable.

The studies reviewed indicate that, although promising technologies are available, their success is dependent on systemic enablers: governance arrangements, user awareness, long-term monitoring and designs that foster inclusion. Accordingly, it is not just the new technologies that need to be developed but also the institutions and systems of knowledge that can facilitate equitable, sustainable adoption of these technologies.

Table 5: Gaps and Future Research Directions for RQ4

Identified Gap	Implication for Future Research	Relevant Citations
Insufficient long-term impact studies of irrigation technologies	Need for longitudinal designs and follow-up monitoring of adopted technologies	Tefera et al. (2024), Johnson et al. (2024)
Limited integration of socio-economic equity in technology assessments	Incorporate poverty, access, and inequality metrics in evaluation frameworks	Villani et al. (2018), Frimpong et al., (2023)
Low documentation of farmer perceptions and behavioral responses	Include behavioral science approaches and participatory methods	Kotze et al. (2024), Ofosu et al. (2013)
Underrepresentation of gender-disaggregated impacts	Apply gender mainstreaming in data collection and reporting	Wildemeersch et al. (2013), Styger & Jaoui, (2022)
Few cross-country comparative evaluations	Standardize metrics for multi-country trials to enable benchmarking	Zondo et al. (2024), World Bank, (2024)
Sparse evaluation of groundwater sustainability under solar irrigation	Model aquifer dynamics and evaluate long-term water balance	RTI International (2022), Innovation: Africa (2024)
Lack of data on cost-benefit ratios under varying farm sizes	Analyze economic efficiency across scales of implementation	Negera et al. (2025), Assefa et al. (2019)
Minimal attention to institutional and governance mechanisms	Investigate policy frameworks and coordination mechanisms	World Bank, (2023), Ahmed et al., (2025)
Low coverage of post-adoption challenges and maintenance	Study operational lifecycle and costs of repairs over time	Babiker et al. (2021), Dawit et al. (2020)
Neglect of indigenous and nature-based irrigation knowledge	Revive and validate traditional systems through mixed-methods research	Okello et al., (2024), Awulachew et al. (2008)
Limited application of real-time digital monitoring at scale	Assess feasibility and scalability of IoT and satellite-assisted systems	Nomugisha & Mwebaze, (2025), Munyaradzi et al. (2022)
Absence of ecosystem service trade-off analyses	Quantify co-benefits and trade-offs with biodiversity and soil health	Frimpong et al., (2023), Biazin et al. (2021)

4. Discussion

4.1 Typologies and Patterns in Sustainable Irrigation Technologies in SSA

According to the findings on RQ1, the typological diversity of irrigation systems used in sub-Saharan Africa (SSA) reflects an attempt to strategically marry water scarcity with the distinct agro-ecological and socioeconomic context of smallholder farming systems. So instead of a technological march, the irrigation landscape of the region is the outcome of layered innovation – traditional coexisting with low tech and developing digital solutions, frequently in overlapping or hybrid ways of use. This pattern suggests a decentralized model of irrigation development, which has been shaped as much by local constraints as by donor agendas and national priorities.

Drip irrigation, for example, dominates studies from Ethiopia, Ghana, South Africa, and Zimbabwe alongside other conservation agriculture practices or solar pumping systems (Assefa et al., 2019; Dawit et al., 2020; Pienaar, 2014). Its popularity is not surprising thanks to its proven performance gains, but its long-term viability continues to hinge on cost-sharing strategies and infrastructure reliability. The "hybridization" of drip and other low-energy technologies, such as hand dug wells or solar pumps, mirrors both farmers' innovation logic and the constraints of single solution approaches in resource-scarce environments.

Solar irrigation, the fastest growing technology class in recent years, marks an infrastructural leap, bridging energy poverty and water access (Birhanu, et al., 2023; RTI International, 2022). But it's ethos is not universally a winning one. The spatial analyses of Negera et al. (2025) or Innovation: Africa

(2024) highlight potentially high intra-regional variation in feasibility, according to groundwater availability, solar irradiance and local community governance capacities. This indicates that even if well aligned with a given adaptation trajectory, the implementation of solar systems should be accompanied by sound resource mapping and post-installation support.

Another important trend is the use of decision-support and scheduling tools such as AquaCrop, CROPWAT, and IoT measurement-based tools. While they hold great technical promise (Too et al., 2020; Biazin et al., 2021), their practical roll-out is still embryonic, and the vast majority of projects completed as of the time of writing concentrate on NGO-led pilots on academic research stations. Shachar repeats this concern: it suggests that we are not certain about scalability of the digitized processes or about the institutional structure that is required to embed digital solutions into everyday patterns of farming. Additionally, adoption by users depends not only on the cost but also on digital skills and trust in the automated system — factors not well covered within the literature.

Concurrently, traditional and nature-based technologies like zai pits, bunds and sand dams, remain prevalent in Sahelian and arid regions (Awulachew et al., 2008; Korodjouma et al., 2017; Demessie et al., 2022). Although simple in appearance, such systems are complex and have important design lessons in resilience and sustainability to offer. Yet, in practice, they tend to be under-resourced and under-studied compared with engineered alternatives, mirroring a techno-centric bias in donor funding and academic research.

Patterns of technologies at region levels also suggest that there are institutional and historical lags in the development of irrigation. Ethiopia has taken most of the implementation landscape, account for more than 30% of the reviewed studies, demanding such large portion due to a mix of political interest, donor money, agro-climatic variation. On the other hand, fragile and post-conflict settings (like Chad or Central African Republic) are extremely under-represented, not necessarily because the needs are lower but because the data are sparse and the research environment is also sub-optimal.

What we find is a distinct plurality of technology routes, determined not only by technical performance, but by access, governance and environmental aptness. The literature we review offers a rich catalogue of interventions, but generally remains larger too committed to innovation at the expense of integration, and often treats technologies in isolation rather than as parts of larger systems of land use, labor and hydrological interdependency. This gap points to a requirement for future reviews to take a systems thinking perspective, which considers the embeddedness of irrigation in socio-ecological systems.

Overall, the technoscape of sustainable irrigation in SSA appears as a dynamic yet uneven terrain. The typologies found indicate adaptation and innovation, but likewise suggest the vital tension between scales of design, justice and sustainability. With new technologies such as 4IR-enabled irrigation and nature-based solutions entering the scene, the question now is whether or not they can be institutionalized through models that are led by, rather than imposed upon, farmers over the long term. Integration of technology innovations with farmers' participation, infrastructure investments with effective governance, and modern technologies and indigenous knowledge is the main challenge and opportunity for advancing irrigation development in SSA.

4.2 Impact of Irrigation Technologies on Water Productivity and Crop Yield across SSA Contexts

The analysis of the heterogeneous effects of sustainable irrigation technology on WUE and yield in Sub-Saharan Africa addressed under RQ2, does not rely only on mean values. While the results showed that drip irrigation and solar technology are superior on average, more careful scrutiny reveals that these gains are uneven and are strongly conditioned by ecological suitability, infrastructure maturity, and social-economic readiness.

Drip was the (perceived) best water-efficient technology, followed by the mean increments for yield (70%) and water productivity (60%). "But its cost-effective is context-specific, as evidenced in research from Ethiopia, Ghana and South Africa (Assefa et al., 2019; Pienaar, 2014; Ncube et al., 2010), the latter of which is affected by how it is managed on farm, the quality of installation and the presence of technical support". In systems with low upkeep or supply interruptions, yield gains can quickly fall off, causing under yielding even in high-yield areas. Moreover, the studies such as Nkya et al. (2015) and

Adeboye (2015) indicate that despite water savings, the real commercial difference may be limited due to market inefficiencies and high input prices.

Solar irrigation, as observed in the studies of Birhanu et al. (2023), Innovation: Africa (2024) and RTI International (2022) produced promising results in countries including Mali and Benin. But the literature also emphasizes the sustainability issue, especially as far as the over-pumping of groundwater is concerned. Although there are great short-term gains in yield (65%) and water productivity (68%), the sustainability of such systems will depend on sound water resource planning and aquifer recharge knowledge — both presumably under-researched at the moment. Furthermore, the performance of these technologies is highly susceptible to regional factors, such as the consistency of the solar radiation, where the latter can vary within semi-arid areas.

02 Tools and technologies Scheduling tools and IoT based-system, as ones implemented in Kenya and Uganda (Too et al., 2020; Nomugisha & Mwebaze, 2025) brought about moderate but sustainable improvements. They are more effective in terms of timing and volume of water applied rather than in adding more water. But their benefits are also disproportionately high in research stations or donor-supported pilots, and quite low in independent farmer trials. This is part of a broader problem of technological drift — that results in experimental test cases not being replicated linearly in a real farming context.

Nature-based solutions, as described in thematic reviews, Frimpong et al., (2023) and Okello et al., (2024), showed only small yield and water efficiency benefits and, conversely, had high resilience to high-risk, low resource environments. Their effect should be recognized not just in agronomic terms, but as ecosystem services — enhancing soil water-holding capacity, biodiversity, and social unity over shared resources. However, such co-benefits are seldom quantified, and consequently, NBS have limited policy visibility, despite high adaptive potential in exposed zones.

The differences across ecological zones were an obvious trend. While technologies that flourished in highland and sub-humid zones (e.g. drip irrigation, conservation agriculture) were not necessarily successful in arid and Sahelian areas, where water harvesting and bunding are more relevant (Wildemeersch et al., 2013; Korodjouma et al., (2017). The context specific nature of impact emphasizes the limitations of one-size-fits-all solutions in irrigation policy. Differential results were also evident country to country, if not, in some cases, within the same country – such as in Ethiopia, where both high-efficiency drip systems and low-efficiency manual pulley-based devices exist (Hussein et al., 2024, Dawit et al., 2020).

The comparatively low yield and productivity increments associated with furrow irrigation (30% yield, 25% water productivity) further justified that furrow irrigation is a temporary and/or fall-back technology (Nkya et al., 2015; Pienaar, 2014). Yet, the fact that it remains a commonly used (if not the most used) technology in Tanzania and South Africa suggests that cost and recognition trump performance indicators for the vast majority of smallholder farmers. This stresses a major message of this paper: performance should not be evaluated solely based on agronomic outcomes but on user limitations and risk aversions.

In statistical terms of dispersion, technologies with higher average impacts (drip and CA) showed also higher standard deviation of outcomes, suggesting more pronounced spread and sensitivities to enabling conditions. Manual and traditional systems, on the other hand, exhibited less variance but at the cost of a moderate reduction in peak performance, indicating a compromise between robustness and reactivity.

The literature reviewed also reveals a thematic bias: the majority of studies focus on yield and water measures, neglecting other dimensions, such as labor gained, nutritional gain, and economic return on invested. While studies such as that of Agricultural Productivity of Solar Pumps (APSU— 2008 Benin) demonstrate a rare but significant case where nutrition effects are integrated into an impact evaluation of irrigation — a path which future research should follow.

Overall, the welfare effects of green irrigation technologies in SSA are large but conditional. They are conditioned by environmental fit, technological readiness, institutional support, and user readiness. The inconsistency in performance across settings underscores the critical nature of context-specific deployment strategies that tweak interventions to microclimatic, cultural, and socio-economic particulars. Accordingly, whilst irrigation technologies have great potential to address these water and yield issues, integrated planning that takes the hardware and combines it with human systems is what will unlock their transformative potential.

4.3 Influence of Technical, Environmental, and Socio-Economic Factors on Irrigation Technology Success in SSA

Findings in response to RQ3 indicate that the success or failure of the implementation of irrigation technologies in Sub-Saharan Africa (SSA) does not depend entirely at the technical merits of a particular intervention but rather is influenced by a network of interrelated factors. These include the technological conceptualization and complexity of the OM technologies, the ecological and agro-climatic context in which the technology operates, and the wider social-economic systems that either facilitate or hinder adoption and out scaling. The findings in Table 4 and Figure 6 demonstrate that a one-size-fits-all is insufficient to predict success, and it is the balance among the enablers and barriers across contexts that determine the performance consequences.

From the technical perspective, maintenance convenience and user training appeared to be important factors for continued adoption. For instance, the compatibility of technologies such as drip irrigation and scheduling tools was found to be consistently high with smallholder farming when combined with proper training and extension support (Assefa et al., 2019; Too et al., 2020). Complex systems such as IoT-sensor irrigation systems on the other hand proved to be promising under pilot conditions (Munyaradzi et al., 2022; Nomugisha & Mwebaze, 2025) but concerns were raised with respect to repairability, calibration accuracy under field conditions and reliance on external technical expertise. These constraints represent a technical ceiling for smallholders, unless systems are simplified or accompanied with ongoing support.

The environmental factor fulfils a dual function here, as help and obstacle to the technological working. For example, solar irrigation systems have a strong reliance on stable solar irradiance and shallow water tables, which can be found in some areas, such as Mali and Ethiopia, but not consistently throughout SSA (Birhanu et al., 2023; RTI International, 2022). In water-stressed Sahelian areas, nature-based solutions such as zai-pits and bunds were well-suited to low rainfall climates and provided ecosystem co-benefits, including soil conservation and erosion control (Korodjouma et al., 2017, Wildemeersch et al., 2013). Conversely, fragility of the environment can also limit interventions: subsurface irrigation technologies tested in Sudan (Babiker et al., 2021) were highly effective from an agronomic perspective but were dependent on soil and hydrological conditions that were rare outside the pilots, suggesting that the technology might have limited potential for scaling.

Social determinants of success were frequently the most powerful discriminators of success and stagnation. Unless followed by subsequent research, the death of these projects concealed the multitudinal contingencies of access to capital, the assurance of land tenure, labor supply, and institutional trust, features that conditioned the preparedness and capacity of farmers toward irrigation engagement. For instance, even high-yielding technologies, such as conservation agriculture-related drip kits, underperformed under the investment was too high or in conditions where credit systems were lacking (Dawit et al., 2020; Negera et al., 2025). Furthermore, its equivalent in community technology such as sand dams and solar village schemes yielded varied results according to the effectiveness of community governance and social capital (Demessie et al., 2022; Innovation: Africa, 2024). In these examples, the technology itself was not the constraint, rather the sustainability of it was dependent on group management processes and clear roles.

An aspect that is particularly under- researched in the literature is the perspective of gender and behaviour. Although "smallholders" are frequently mentioned in socio-economic analysis as a uniform group, it is notably challenging to find studies that have disaggregated data according to gender or provided insights concerning intra-household decision-making (Wildemeersch et al., 2013; Styger & Jaoui, 2022). This lack of fine-tuning conceals differences in the levels of delivery of things like responsibility and access to irrigation technologies within the household or community. In addition, few studies considered behavioural stickiness, risk-aversion and cultural beliefs, which may have an impact on adoption despite the availability of the technology or functional effectiveness of the product.

It is also notable that interdependences of factor sometimes even generated counterintuitive results. Like for example, although mechanical systems (such as manual pulley system) were technically rudimentary, they scored socially and economically high due to their affordability and instant familiarity (Hussein et al., 2024). On the other hand, developed systems such as the solar-IoT packages, while environmentally friendly and technically superior, often suffered from a lack of user education or had trouble surmounting organizational obstacles. This result indicates that it is appropriateness, rather than sophistication, that should inform technology transfer and scaling approaches in SSA.

At the policy level, low support from institutions and fragmented policy often came up as one of the barriers, in particular for technologies that are in need of wider inter-sectoral coordination (for instance water rights, energy subsidies, extension service). The review of the performance of large-scale schemes by Ahmed et al., (2025) emphasized that lack of maintenance regimes and working capital was the reason they fell into disrepair in many cases. Therefore, sustainability needs to be reimagined as being less a relative static measure of performance, and more as an emergent property of a contextually sustainable technological ecosystem that is well-supported.

These patterns are visually confirmed in the categorical heatmap (Figure 6) in which technologies such as drip irrigation, conservation agriculture and water harvesting have a high rating across all 3 dimensions, whereas clay pot irrigation and subsurface systems demonstrated an uneven alignment in which the environmental suitability was not matched by social-economic scalability. This sophisticated perspective permits more precise targeting of technologies not by universal promotion, but appropriate tech profiling based on location specific ecology, farmer type, and institutional preparedness.

In sum, the story of successful sustainable irrigation technologies in SSA is path-dependent, and contingent upon a multilayered ecology of enabling and constraining factors. Technologies need to be socially embedded, ecologically fit, and institutionally supportable. This being the case, policymakers and development practitioners should adopt a more diagnostic form of irrigation planning that values local capacity building, the interactions among systems, and feedback, rather than assuming linear impacts of mere hardware installation.

4.4 Gaps in the Literature and Implications for Future Research and Policy in SSA Irrigation

Despite being increasingly rich in techonological innovation and local impact evaluations, findings in response to RQ4 indicate that the sustainability landscape of irrigation research in Sub-Saharan Africa is still very much characterised by substantial structural and content-related gaps. These deficiencies – from analytical gaps to blind spots in the field – materialise as serious limits to the strategic scaling, integration and sustainability of irrigation interventions in the long run. As depicted in Figure 7, these gaps provide a focus for a targeted research agenda or policy reform trajectory to bridge the conditions that need to be met in moving from disconnected innovation to systemic transformation.

They particularly lack long-term follow-up studies on irrigation to evaluate the effect of irrigation over time. Although research such as that by Assefa et al. (2019) and Dawit et al. (2020) provide strong short-term assessments of drip and conservation technologies, but rarely show how performance metrics change across seasons or with a history of climatic fluctuation. This time lag restricts our ability to assess durability, scalability and technology fatigue—especially amongst erratic rainfall poses or shrinking groundwater stores. Future inquiries will consequently need to be for the long term, including ideally within national agricultural extension systems, to follow up on dynamic change and inform flexible policy.

Equally urgent is the under examination of equity, inclusion, and gendered aspects related to irrigation access and outcomes. Notwithstanding evidence from Wildemeersch et al. (2013) and Styger & Jaoui, (2022) that adoption and intra-household distribution of benefits are shaped to a great extent by socio-cultural factors, the majority of studies included in the review do not reveal gender-, age-, or socio-economic specific results. And by homogenizing, it discourages us from understanding who wins and who is losing. A concerted shift towards gender-responsive and equity-driven research is needed, not only for scholarly integrity but to identify targeted subsidy, training and outreach programs.

A second noteworthy gap involves omission of the behavioral and perceptual aspects of adoption. Such investigations as Munyaradzi et al. (2022) and Nomugisha & Mwebaze, (2025) demonstrate the influence of user perception on technology acceptance, especially digital systems. However, relatively few studies systematically address farmer attitudes, risk preferences, or decision-making heuristics. This is quite significant, as behavior frequently serves as an intermediary by which technological capability is translated into real-world functionality. Research moving forward must be partnered and mixed methods, using behavioral economics and rural sociology to inform interventions that make sense on the ground.

The reviewed literature is also limited by the absence of standardized cross-regional comparisons. Inter-unit generalization is often made without evidence in relation to the transferability of a technology tested in one eco-geographic zone (e.g., highland of Ethiopia) to other zones. While multi-country projects such as Innovation: Africa (2024) and Frimpong et al., (2023) offer generalist reviews, they lack methodological rigour suitable for informing policy across boundaries or programmes that are regionally harmonized. There is a great need for controlled, multi-site studies with standardized outcome measures. They would provide further evidence-based scaling opportunities and avert the traps of one-size-fits-all interventions.

Additionally, the literature reviewed does not sufficiently capture economic sustainability, especially long-term cost-effectiveness and what gets back by technology scale. Though cost-reduction and production-improvement successes are commonly communicated, few conduct cost-benefit modeling that encompasses farm sizes and financible structures. This is an unfortunate oversight as cost and financial sustainability are also fundamental obstacles to adoption. It is recommended that, in the long-term, performance comparison studies should include farm economics into the evaluation process, particularly lifecycle costs but also the analysis of different financing strategies such as pay-as-you-go or shared ownership models.

A third blind spot is governance and institutional arrangements. Although irrigation success is widely recognized to depend on regulatory facilitation, land tenure clarity, and service delivery coherence, such enablers continue to be analytically sidelined. The handful of papers that do focus in on these dimensions (see, for example, Performance of Large-Scale Schemes (Ahmed et al., 2025)) have confirmed the importance of both maintenance regimes and cross-sectoral policy harmonization. Potential approaches for future scholarship include expanding beyond agronomic benchmarks and focusing on institutional architecture, stakeholder coordination, and accountability mechanisms as underlying cornerstones of sustainable irrigation.

One especially neglected issue is knowledge integration with traditional management of water. Systems such as zai pits and bunds are relatively well-documented (Awulachew et al., 2008; Korodjouma et al., 2017), but with limited validation, improvement, and integration into modern systems. Resurrecting and transforming local ecological knowledge may add not only cultural legitimacy but also climate-adapted practices that were the output of generations of learning from the environment itself.

Finally, digital and remote-recording practices are making inroads in irrigation systems. But evidence-based research that critically examines their scalability, affordability, and likelihood of success in different contexts remains scarce. The majority are relegated to pilot phases or textbook examples. As Figure 7 underscores, prospective real-time digital surveillance systems must be weighed against an understanding of technology readiness, Harder Storage systems, infrastructure and rural, digital literacy.

On the whole, this reveals a discipline in transition: enthusiastic experimentation but fractured direction. The deficiencies we have clearly highlighted are not simply academic— they have real implications for resource allocation, project assessment and peasantry experience of irrigation “on the ground”. Filling these gaps will require a reorientation of irrigation research from a technocratic one toward a systemic, inclusive, and context-specific paradigm. Only by making such a switch we will be able to unlock the potential of irrigation to contribute fully to food security, climate resilience and inclusive rural area development in SSA.

5. Conclusion

Based on a thorough examination of 50 peer-reviewed studies within Sub-Saharan Africa (SSA), this SLR offers a comprehensive review of sustainable water engineering and irrigation technologies developed to counter water scarcity with smallholders in mind. Adopting the PEO and impact-effectiveness frameworks, the appraised assessed what technologies were used, their efficacy, the contextual factors that drive outcomes, and the outstanding challenges that hinder the scaleable, equitable and resilient irrigation solutions in the region.

The evidence confirms that SSA is undergoing the diversification of it's irrigation technology mix, not only to include drip irrigation, but also solar pumps, water harvesting structures, conservation agriculture and new ICT tools such as IoT and decision support software. These technologies show marked average benefits in water productivity and crop yields, particularly in upland and semi-arid agro-ecological areas. But their effectiveness is extremely mixed and depends at the intersection of a number of environmental, technical, and socio - economic factors, such as groundwater availability, user training, cost recovery, and the ability to govern.

Most crucially, the review reveals institutional voids that prevent irrigation from fully realizing its potential. These are the lack of follow-up, poor integration of gender and equity, underdeveloped behavioral dynamics, inadequate cross-country comparison, and limited focus on institutional structure and indigenous knowledge. Moreover, the swift scale-up of digital and solar technologies market-based innovation also exceeds the readiness of rural systems to cope with them and ensure their sustainability and question of appropriateness and inclusivity.

In order to better inform academic inquiry and policy action, the SLR calls for integrated approaches to align technological innovation with user realities, ecological limits and institutional support structures. Irrigation development in SSA needs to move from projectized, one-size-fits-all interventions to adaptive, participatory and system-aware interventions. This would require redefining research agendas to fill knowledge gaps, improve monitoring systems to measure long-term results, and integrate equity and resilience into irrigation planning and investment.

In the end, a sustainable irrigation in SSA will not be a matter of diffusion of appropriate technologies, but on building the necessary enabling environment—including informed policy, responsive research, and active smallholder communities. This review provides a timely and strategic context for these efforts and will serve as a roadmap for research, development programming, and regional cooperation toward securing water and food systems in an era of rapidly increasing climate and demographic pressure.

6. Policy Implications

What the evidence presented in this review has shown, is that this moment is long overdue particularly in terms of policy frameworks in SSA that are responsive not just to technological possibilities but also to the contexts that drive irrigation adoption and sustainability. Policymakers need to shift from isolated interventions to integrated ones across sectors that assure long-term sustainability, equity and scalability of sustainable irrigation systems.

6.1 Promote Fit-for-Context Irrigation Planning

More broadly, policies need to facilitate and encourage context-specific irrigation planning that incorporates agro-ecologically suitability, groundwater mapping and socio-economic profiling. Instead of uniform prescriptions, irrigation plans should be developed on a micro-zone basis, and also consider indicators to monitor environmental risks such as the declining of aquifers or salinization. The national ag-ext systems need to be enhanced to serve as the vehicles to facilitate decentralized decision-making and technology adaptation on the basis of local evidence.

6.2 Expand Inclusive Financing Models

High cost of modern irrigation technologies including powered by solar and drip system is one of the main constraints of the smallholder farmers. Policy should promote inclusion-in lending schemes such as smart subsidies, micro-credit and pay-as- you-go models prioritizing female farmers and low-income households. Public–private partnerships (PPPs) can be crucial in de-risking investments and in increasing access to irrigation infrastructure, particularly in remote and underserved regions.

6.3 Institutionalize Monitoring and Longitudinal Impact Assessment

This requires the institutionalization monitoring and evaluation component, it is important of measuring BCC program impacts.

To promote transparency, learning, and accountability, long-term monitoring and evaluation of government and donor irrigation interventions should be institutionalized. This includes developing common performance indicators to measure not just agronomic results but also profitability, equity issues and environmental impacts. Digital channels and mobile-based applications can be used for real-time data generation and farmer response mechanisms.

6.4 Mainstream Gender and Equity in Irrigation Governance

Policies need to move beyond 'token' gender inclusion towards gender-responsive irrigation governance. This involves not only counting women in water user associations and decision making bodies, but reimagining technologies and service delivery to incorporate gendered labor dynamics, access to land, and control over assets. Data collection and impact assessment (disaggregated) must be made mandatory in all the government and donor funded irrigation projects.

6.5 Invest in Capacity Building and Behavior-Centered Design

Education schemes for cultivators/technicians/extension workers must constitute an integral part of irrigation expansion systems. Yet training should not merely focus on technical proficiency – it should also facilitate behavioural insights, trust and participatory design. Experimentation and farmer-run demonstration plots must be scaled up to promote learning-by-doing, and policies should promote feedback loops between users and technology suppliers.

6.6 Strengthen Cross-Sectoral and Transboundary Coordination

Successful irrigation policy is consistent across water development, agriculture, energy and land governance. To harmonize regulation, expedite approvals and avoid policy inconsistencies, ministries and regulatory authorities need to institute inter-agency coordination platforms. At the regional level, irrigation planning should be incorporated into shared basin management frameworks, as well as climate adaptation plans.

6.7 Incorporate Indigenous Knowledge and Nature-Based Solutions into Management

Ensure that traditional knowledge and restorative approaches intended to further the fish population's recovery are considered throughout the management process (that is establishment of scientific stock assessment-based fishery targets, regulations, among others).

New technologies must be complemented by policies that acknowledge and support traditional and ecosystem-based water management. This should scale up field-tested methods, such as zai pits, earth bunds and sand dams, as well as building documentation, validation and adaptation of LFIs into national research and training programs. Nature-based solutions are often as, or more, cost-effective and climate-resilient than engineered solutions in ecologically sensitive areas and should be prioritized in public funding channels.

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