ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2521-294X (Online)
ISSN: 2521-2931 (Print)
CODEN: MJSAEJ

Malaysian Journal of Sustainable Agriculture (MJSA)

DOI: http://doi.org/10.26480/mjsa.02.2026.62.69

RESEARCH ARTICLE

WATER-SAVING IRRIGATION STRATEGIES FOR SUSTAINABLE RICE FARMING IN KEDAH, MALAYSIA

Ousman Ceesay*, Norizan Azizan

School of Business and Social Sciences, Albukhary International University, Jalan Tun Razak, 05200, Alor Setar, Kedah, Malaysia
Corresponding Author Email: ousman.ceesay@student.aiu.edu.my

ARTICLE DETAILS

Article History:

Received 26 January 2026
Revised 20 February 2026
Accepted 25 February 2026
Available online 08 March 2026

ABSTRACT

Kedah's Muda Agricultural Development Authority (MADA) is the centre for Malaysia's rice production and is now under immense stress due to water scarcity, climate variability and livelihoods of smallholder farmers. There are three water-saving irrigation techniques that could be used to help with this problem; AWD (Alternate Wetting and Drying), SRI (System of Rice Intensification) and precision irrigation. These irrigation methods have been shown to be effective, however the adoption has been low and it is not clear what are the socio-economic and institutional barriers to adoption or how policy and governance are affecting the use of these irrigation techniques in Kedah and other similar rice-producing systems in Asia.

This study uses a systematic review to synthesize data from 85 studies published in 2015-2025 (see appendix for details) using a PRISMA 2020 protocol to evaluate the impacts of AWD and SRI and to understand the barriers to adopting AWD and SRI as well as the governance structures affecting their implementation in Malaysia. The review found that both AWD and SRI can significantly reduce irrigation water use and maintain or increase crop yields; they also provide additional environmental benefits including reduced methane emissions and improved soil health. Data from local MADA pilot programs indicate that these results can be replicated in the climate and conditions of Kedah, however the rates of adoption remain very low, which is consistent with an "effectiveness - adoption" paradox caused by a number of factors including but not limited to: lack of access to capital; inadequate extension services; risk aversion among farmers; and the aging population of farmers, gender inequity, and division of responsibilities within government institutions, none of which are directly related to the technology itself.

Technical viability and local relevance of water-saving irrigation strategies have been demonstrated in the review; however, their successful adoption by farmers at a large scale is contingent on a combination of coordinated, systemic policy actions. To this end, integrated initiatives that enhance the capacity of extension services, reduce economic risks associated with irrigated agriculture for both male and female farmers, and provide alignment of governance among agencies will be necessary to realize the technical potential for sustained use of these technologies among farmers. These types of reforms are essential for improving water security, climate resilience, and livelihoods for small-scale farmers in Kedah and other similarly dependent rice producing areas.

KEYWORDS

Water-saving irrigation, Sustainable rice farming, Muda Agricultural Development, Authority (MADA), Kedah Malaysia, Alternate Wetting and Drying (AWD), System of Rice Intensification (SRI), Precision irrigation

1. INTRODUCTION

Water consumption associated with the production of irrigated rice is among the highest of all agricultural products worldwide with irrigation accounting for 40-50 percent of all freshwater used in irrigated agriculture (Tuong and Bouman, 2003). Therefore, it is critical to develop methods to sustainably produce rice and reduce its demand for water to meet increasing demands for water for other purposes related to population growth, urbanization and environmental degradation (World Bank, 2022). Climate change has increased the difficulty of sustaining rice production by changing the frequency and duration of drought and flood events that impact traditional irrigation practices and increase the vulnerability of water dependent rice production systems (IPCC, 2019). Thus, improving water productivity (i.e., producing more rice per unit of water) has been identified as a major strategy to sustain food security, enhance climate resilience and maintain the livelihoods of small-scale farmers who grow rice in tropical areas (Tuong and Bouman, 2003).

As a result, rice is of strategic significance to food security policies in Malaysia. Kedah State is particularly important because of its contribution to national rice production via the Muda Agricultural Development Authority (MADA) irrigation scheme which is one of the largest gravity fed irrigation schemes in Southeast Asia (DOSM, 2023; MADA, 2024). MADA provides irrigation services to over 100,000 small-scale farmers who operate on land parcels that are too small to be economically viable without irrigation (DID, 2023). Consequently, the sustainability of irrigation systems in Kedah has implications for the nation's food supply.

To address concerns regarding the sustainability of irrigation systems in Kedah, there is interest in developing alternative irrigation strategies that conserve water such as Alternate Wetting and Drying (AWD), the System of Rice Intensification (SRI) and precision irrigation. International and regional research has shown that these water-saving irrigation strategies

Quick Response Code	Access this article online	
	Website: www.mjsa.com.my	**DOI:** 10.26480/mjsa.02.2026.62.69

Cite The Article: Ousman Ceesay, Norizan Azizan (2026). Water-Saving Irrigation Strategies for Sustainable Rice Farming in Kedah, Malaysia. Malaysian Journal of Sustainable Agriculture (MJSA), 10(2): 62-69.

can significantly reduce irrigation water usage while either maintaining or increasing crop yield and provide additional environmental benefits including reductions in greenhouse gases and improvements in soil health (IRRI, 2020; Lal, 2016). Local pilot projects conducted by MADA have also demonstrated the feasibility of implementing water-saving irrigation strategies in Kedah's agroecological and infrastructural environment (MADA, 2024).

Despite the demonstrated effectiveness of these water-saving irrigation strategies and government support, adoption of these strategies by small-scale farmers in Kedah remains low and irregular. Adoption has primarily occurred through pilot projects and/or subsidized programs with little diffusion into normal farm management practices. This disparity between the technical potential and farmer adoption of water-saving irrigation strategies illustrates the need to consider the social, economic and institutional factors that influence irrigation decision-making processes in addition to the technical characteristics of irrigation strategies (Rogers, 2003; Ostrom, 2010).

Given this, the purpose of this study is to synthesize research on water-saving irrigation strategies for rice in Kedah and other similar rice growing environments to better understand the relationships between the technical characteristics of water-saving irrigation strategies, the dynamics of farmer adoption and the governmental policies that affect the ability to achieve sustainable and climate resilient rice production.

1.1 Problem Statement

The use of water-saving irrigation strategies for rice production in Kedah's MUDA region is seen as a promising way to address both water scarcity and climate variability challenges currently faced by the rice sector in Malaysia (Othman et al., 2015; van Kalken et al., 2019; and NARBO/IGES, n.d.). There is a body of literature that examines the technical and agronomic potential of water saving irrigation strategies, but very little work has addressed the issue of how these strategies can be adopted in practice at the level required to achieve significant improvements in the water productivity of the rice crop. The literature does however provide some useful insights on the factors that influence the rate and extent of adoption of new agricultural technologies (Othman et al., 2015; and Mokhtar et al., 2022). These include the degree to which the farmer perceives that the technology will benefit them financially; the degree of uncertainty surrounding the likely outcome of using the technology; the availability of information and advice on how to adopt the technology effectively; and the degree to which the technology fits with existing social and economic systems.

A number of studies have shown that when farmers in developing countries have had access to appropriate levels of technical information and financial incentives they have been able to successfully adopt new irrigation technologies that save water (Chew et al., 2023; Pronti et al., 2024). Examples of such technologies include the alternate wetting and drying of paddies (AWD); the system of rice intensification (SRI); and precision micro irrigation systems. While the results of these studies suggest that it may be possible to achieve widespread adoption of water-saving irrigation strategies for rice in Kedah's MUDA region, they do not provide much detail on how best to facilitate the process of adoption at the level of individual farmers.

One major factor limiting the development of effective policies to support the adoption of water-saving irrigation strategies for rice in Kedah's MUDA region is the existence of multiple agencies involved in the provision of irrigation services, subsidies and extension advice to rice farmers. Each agency has its own priorities and procedures for providing services to farmers, which creates a complex environment in which to implement policies to promote the adoption of new irrigation technologies (Amran et al., 2020).

Another factor limiting the ability of the state to develop effective policies to support the adoption of water-saving irrigation strategies for rice in Kedah's MUDA region is the gender-based inequality that exists in the distribution of opportunities and resources available to rice farmers (Avil Kumar and Rajitha, 2019; Lei et al., 2024). Women make up a large proportion of the workforce engaged in rice production in Malaysia, yet they typically have limited access to training and decision-making support compared to men.

There is therefore a need for a systematic evaluation of the impact of socio-economic and institutional conditions on the effectiveness of policies designed to promote the adoption of water-saving irrigation strategies for rice in Kedah's MUDA region (Amran et al., 2021; Mwalyagile et al., 2024). Such an evaluation would require a mixed-methods approach that integrates data and insights from a range of sources including literature reviews; surveys and interviews conducted with rice farmers, government officials and private sector companies; and field observations of the operations of irrigation systems and the implementation of policies to promote the adoption of water-saving irrigation technologies (Arabiyat, 2005).

While previous studies in Malaysia have investigated irrigation efficiency and agronomic performance, the literature lacks an integrated assessment that systematically links the technical effectiveness of water-saving irrigation strategies to the socio-economic and institutional environments that affect their large-scale adoption. To understand why proven technologies are still underutilized, an analytical approach must integrate technological adoption behavior with policy and governance dynamics (Davis, 1989; Rogers, 2003). It is also important to design intervention strategies that help build climate resilience, support smallholder livelihoods and enable the transition to sustainable rice production in Kedah.

Therefore, this study conducts a systematic review of secondary evidence from 2015 to 2025 to assess the water-saving irrigation strategies in Kedah's MADA Regions I-III. Through the integration of concepts from Technology Acceptance Model, Diffusion of Innovation Theory and Polycentric Governance Perspectives, the study aims to produce evidence relevant to policymaking to support the transformation towards more sustainable and inclusive rice production in Malaysia.

1.1.1 Research Objectives

- To evaluate the effectiveness of water-saving irrigation strategies, Alternate Wetting and Drying (AWD), System of Rice Intensification (SRI), and precision micro-irrigation in improving water productivity, rice yields, and environmental outcomes in rice systems relevant to Kedah's MADA Regions I–III.
- To analyse the socio-economic, behavioural, and institutional factors influencing smallholder adoption of water-saving irrigation strategies in Kedah.
- To assess the extent to which existing agricultural policies and governance arrangements support or constrain the scaling of water-saving irrigation technologies in Kedah's rice sector.

1.1.2 Research Questions

- How effective are AWD, SRI, and precision irrigation strategies in enhancing water productivity, yields, and environmental performance in rice systems comparable to Kedah's MADA Regions I–III?
- What socio-economic, behavioural, and institutional factors shape smallholder farmers' adoption of water-saving irrigation strategies in Kedah?
- How can agricultural policies and institutional coordination be strengthened to support wider adoption of water-saving irrigation and climate-resilient rice production in Kedah?

2. Literature Review

2.1 Rice Production, Water Use, and the Sustainability Challenge

At the same time, it is also among the most water-intensive agricultural activities, which accounts for about 40-50% of all fresh-water withdrawal in irrigated agriculture globally (FAO, 2022). In Malaysia, this contradiction between food security and water sustainability is particularly obvious in Kedah, which is recognized nationally as the "rice bowl." Through the Muda Agricultural Development Authority (MADA) grainery, Kedah supplies a significant portion of the national paddy harvest. Production of paddy is largely based upon small-scale farming units averaging 1-2 ha (DOSM, 2023; MADA, 2024).

Continuous flooding irrigation is the historically dominant method of rice production in Kedah and much of Asia, dating back to the Green Revolution, to grow high yielding varieties, suppress weeds, and stabilize crop yields. Although flood-based rice cultivation has provided reliable crop yields for several generations, it has been identified by the literature as being environmentally unsound and economically unproductive due to current circumstances of water scarcity and climate variability. Typical flooded rice systems apply between 3000-5000 liters of water per kg of milled rice but have low water productivity and lose a large portion of applied water through percolation, seepage, and evaporation (Tuong and Bouman, 2003; FAO, 2022).

The environmental consequences of continuous flooding rice systems are well-documented. The flooding causes anaerobic soils leading to increased methane emission levels contributing to agricultural greenhouse gas levels. Excessive surface water application and supplemental

groundwater extraction have led to accelerated aquifer depletion in many Asian rice growing regions. Climate change has increased the pressure on these systems and has demonstrated its impact on the region. Recent experiences in Kedah demonstrate the impacts of climate change. For example, in 2024, floods destroyed approximately 6000 hectares of paddy and in 2025, early season flooding posed a threat to national production. Notably, both droughts and floods expose farmers using traditional flooding methods to extreme weather conditions -- reduced irrigation availability leads to droughts, and excess water overwhelms drainage systems. This exposure to climate extremes has created an urgent need for water efficient systems that will provide enhanced climate resilience (Abdullah, 2019).

In response to the pressing global concern regarding water conservation and increasing water usage in rice cultivation, researchers and policymakers have focused their attention on water saving irrigation techniques. Water saving irrigation techniques aim to decrease the relationship between water use and rice production while either maintaining or increasing rice yield and environmental performance. Three commonly studied irrigation techniques include Alternate Wetting and Drying (AWD), the System of Rice Intensification (SRI), and precision micro/drip irrigation systems.

2.2 Water-Saving Irrigation Strategies and Their Performance

Most experts consider Alternative Wetting and Drying (AWD) to be the most easily scaled water-conserving strategy for irrigated rice systems. Developed through international research and promotion, AWD alters typical flood-based irrigation regimes by introducing intermittent drying periods to defined soil moisture thresholds prior to re-irrigation. All studies examining AWD have reported that this method of irrigation decreases total irrigation amounts while keeping soil moist during the critical growth stages of the crop. In addition, AWD has been demonstrated to decrease irrigation water usage by an average of 25-35% across a variety of settings in Asia, with average reductions of 28% documented in Vietnam, Bangladesh and the Philippines (Tuong and Bouman, 2003; IRRI, 2020).

In addition to reducing water consumption, AWD has been proven to provide several environmental benefits. Periodic soil aeration eliminates anaerobic conditions which generate methane, thus decreasing greenhouse gas emissions when compared to continuous flooding. Studies have also indicated that AWD is economically beneficial to small-scale producers, since it does not require large investments and provides cost-savings via lower pumping and labor costs. Due to its relatively low-cost, compatibility with current infrastructure and quick payback period, AWD appears to be a viable alternative for small-scale producer dominated rice systems such as those found in Kedah.

The System of Rice Intensification (SRI) represents a more radical deviation from conventional rice agriculture. While AWD focuses primarily on altering irrigation schedules, SRI incorporates modifications to seeding rates and plant densities, soil fertility management and water application into its practices. The majority of empirical studies conducted throughout Asia, Africa and Latin America have demonstrated significant increases in rice yields using SRI, along with decreases in water use and improvement in soil biota (Lal, 2016; Shamshiri, 2018).

Although there is evidence that SRI has the potential for significant agronomic gains, the literature indicates several limitations to its adoption. Typically, SRI practices require additional labor, especially during transplanting, and a higher level of technical knowledge and management precision. Both of these factors contribute to the increased perceived risk of adopting SRI practices and the decreased ease of adoption, especially for aging farm families and households that lack available labor. Consequently, SRI adoption has generally occurred at a slower rate than AWD and is concentrated primarily among early adopters, organized farmer associations, and externally funded pilot projects.

Precision micro- and drip irrigation systems are the most technologically advanced water conserving methods described in the literature. Through the direct delivery of water and nutrients to the root zone, these systems can produce significant reductions in water use while producing nutrient use efficiencies. Several experimental trials have demonstrated significant water productivity gains and reductions in methane emissions and nutrient leaching through the use of precision irrigation systems. However, precision irrigation systems are generally associated with high capital costs, technical complexities, and maintenance requirements that exceed the capacity of most small-scale rice farmers. As a result, the adoption of precision irrigation systems in rice production systems is limited and is generally restricted to high-value crops, larger farms, and subsidized demonstration sites (FAO, 2022).

Table 1: Comparative Performance of Water-Saving Irrigation Strategies

Strategy	Water Savings	Yield Impact	Methane Reduction	Capital Cost	Scalability
AWD	24–35%	+10–12%	~30–45%	Low	High
SRI	20–30%	+20–40%	~30–45%	Low–Medium	Medium
Precision Irrigation	>40–50%	Mixed	Significant	High	Low

Considering the above information, the literature demonstrates a clear order of magnitude of technological feasibility for small-scale farmers: AWD provides high returns on investment with low barriers to entry; SRI may provide greater returns on investment but with added complexity; and precision irrigation will provide the highest water use efficiencies, but the economic and technical constraints faced by small-scale rice farmers limit its feasibility.

2.3 Technology Adoption and Governance Perspectives

The success of water-saving irrigation methods has been demonstrated through numerous agronomic studies however the literature emphasizes that the technical feasibility of an innovation does not necessarily equate to its adoption. As such, technology acceptance theories have provided a basis for understanding why many seemingly promising innovations do not diffuse widely amongst smallholder farmers.

The Technology Acceptance Model (TAM) suggests that the perceived usefulness and perceived ease of use of an innovation are two primary drivers of technology adoption. Therefore, from a TAM perspective, irrigation methods like AWD are likely to be well aligned with the priorities of farmers since their benefits can be readily observed, their application is relatively straightforward and they pose a low risk to farmers. Conversely, irrigation methods such as SRI and precision irrigation tend to rank lower on the dimension of perceived ease of use based on their high labour demands, high learning requirements and high capital costs thereby reducing the likelihood of their adoption (despite possible increases in productivity) (Davis, 1989).

The Diffusion of Innovations (DOI) framework provides additional insight into how adoption occurs and identifies five key attributes which affect the rate of adoption: relative advantage, compatibility, complexity, trialability, and observability. AWD performs well in relation to all of these attributes except possibly for compatibility where SRI and precision irrigation may also perform poorly and therefore experience difficulties relating to trialability, delayed benefits and limited observability at scale (Rogers, 2003).

Moreover, DOI theory emphasizes the role of social learning and peer networks in facilitating the process of diffusion in the case of irrigation technologies — factors which are often absent or weak in fragmented smallholder landscapes (Nunan et al., 2012). At an institutional level, polycentric governance theory highlights the significance of coordination failure in relation to multiple agencies involved in water management, agricultural policy and farmer support. Water saving transitions require a coordinated effort among infrastructure managers, extension service providers, incentive structures and farmer decision makers. Where agency responsibilities are fragmented and incentives are misaligned, even innovative technologies will face significant barriers to scaling (Ostrom, 2010; Nunan et al., 2012).

2.4 Kedah and the MADA Granary: Local Context and Adoption Patterns

The MADA irrigation system is among the world's largest gravity fed irrigation schemes and supports more than 100,000 small-scale rice producing farmers in Kedah's rice growing regions. While MADA is a significant system, it has a relatively low level of water-use efficiency due

to aging infrastructure, unlined channels and continuing dependence upon flood irrigation techniques. In addition to the impacts of plot size and the level of farmer fragmentation on regional water resource pressures, supplemental groundwater pumping adds additional stress to these resources (DID, 2023; MADA, 2024).

Water saving irrigation strategies have been shown through pilot projects within MADA to be technically feasible in local agricultural environments. All pilot projects showed consistent results with AWD trials reporting reductions in water usage and improved or stable crop yields along with lower production costs particularly during periods of drought. SRI pilot projects were found to produce positive results concerning both crop yields and soil health, however they reported significant labor and knowledge limitations which appear to be contributing to limited adoption potential. Precision irrigation was found to provide large water savings however experienced soil compatibility issues and maintenance difficulties particularly in peat based soils.

While the above mentioned pilot projects have documented benefits, adoption is still variable. Adoption of AWD has increased but is still far from universal for SRI and precision irrigation, it is currently marginal. The discrepancy between proven technical feasibility and actual adoption illustrates why the socio-economic and institutional factors impeding wider adoption of these technologies need to be examined as well as their technical performance.

2.5 Socio-Economic, Gender, and Institutional Barriers

Socioeconomic limitations were identified as major impediments to adopting water conservation strategies across many studies. Due to their generally low income and limited access to credit; small-scale farmers are exposed to significant risks related to their crop yield (Pronti et al., 2024). Although costs for implementing water conserving technologies are typically relatively low; it is still difficult for farmers to evaluate whether or not such investments will be cost effective if there is a lengthy time period before they will receive any returns on those investments. The amount of labor available to adopters also impacts the likelihood of adoption. Labor-intensive approaches require additional resources (time) that farmers may not have available to them (Abdullahi, 2022).

The human capital issues that affect the ability of farmers to adopt water conservation strategies include aging farmer population, varying levels of literacy among farmers, and inadequate extension services that provide technical assistance to farmers. Extension service provider-to-farmer ratios are significantly lower than what is considered ideal for effective extension service delivery in Kedah, which limits the number of opportunities for farmers to interact with extension service providers and ultimately reduces the opportunity for extension service providers to influence the behavior of farmers through education(GAO, 2020, DOSM, 2022).

Additionally, women are disproportionately affected by socioeconomic issues that impede the implementation of water conservation strategies. Women are responsible for an estimated 60-80% of the labor associated with rice production, however they are under-represented in training programs, decision making forums, and in access to credit. This has led researchers to recognize that ignoring gender differences in addition to reducing equity also limits the full potential of technology adoption and system efficiency(U.S. Government Accountability Office [GAO], 2020).

In terms of institutional issues, misaligned policies create disincentives to adopt water-conserving technologies. Policies that use price supports to stabilize farm incomes and subsidies to stabilize farm prices can incentivize farmers to continue producing at current levels rather than improving their water use efficiency. Additionally, fragmented governance creates a lack of accountability for achieving improved water productivity and limits the coordination of climate, water, and agriculture-related policies.

Table 2: Adoption Barriers and Corresponding Policy Responses

Barrier Category	Key Constraints	Recommended Policy Response
Financial	Limited credit, upfront costs	Subsidized loans, crop insurance
Human Capital	Aging farmers, low literacy	Targeted extension training
Risk Perception	Fear of yield loss	Farmer demonstrations, peer networks
Gender Inequity	Women excluded from training/credit	Gender-inclusive program design
Institutional	Fragmented agencies (MAFI, DID, MADA, DOA)	Coordinated governance framework

2.6 Synthesis and Research Gap

The majority of the literature demonstrates substantial and consistent evidence that water-saving irrigation strategies (WSIS) can dramatically increase water productivity, enhance environmental performance, and possibly boost farmer income in rice-based systems when applied appropriately. Nonetheless, the literature indicates there is a considerable distance between the technical potential of WSIS and the real-world application of WSIS, especially in regions with a large proportion of small-scale farmers, such as Kedah (Pronti et al., 2024; Chew et al., 2023).

Much existing research has focused on the technical aspects of WSIS and have paid relatively little attention to how farmer behavior, institutional arrangements, and incentive structures interact (Othman et al., 2015; NARBO/IGES, n.d.). Gender disaggregated analysis and governance oriented studies are limited in Malaysia. The literature review suggests that integrated assessments that synthesize technical, socio-economic and institutional evidence are needed to develop scalable, context sensitive interventions to address these knowledge gaps (Lei et al., 2024; Ojo et al., 2021).

Figure 2. Integrated Conceptual Framework for Water-Saving Irrigation Adoption in Kedah

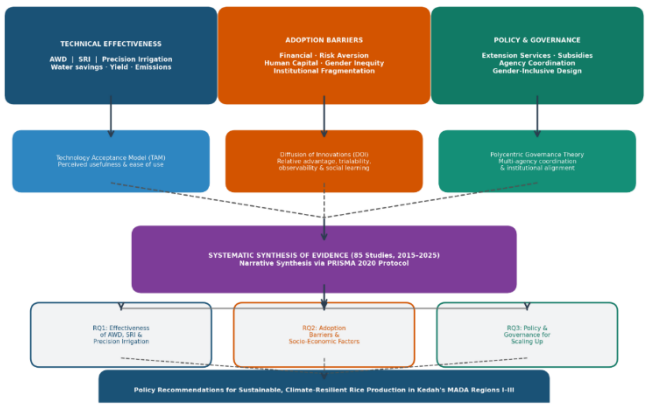

Figure 1: Integrated Conceptual Framework

This study will respond to the knowledge gap identified above by conducting a systematic review of evidence related to water-saving irrigation strategies (WSIS) used in Kedah's MADA Region's I-III to assist in developing more coherent policy and practice pathways for sustainable and climate resilient rice production.

3. METHODOLOGY

3.1 Research Design

The methodology used in this study is a systematic review of existing literature to evaluate the efficacy, adoption impediments and the resultant policy implications of water-efficient irrigation methods in use on rice farms in the Muda Agricultural Development Authority (MADA) Regions I-III of Kedah. The reason for using a systematic review as an approach to provide policy relevant information on the irrigation practices of smallholder rice farmers in these regions is due to the fact that there are numerous studies being completed to assess various aspects of rice production such as, agronomic performance, socio-economic barriers and institutional governance. A systematic review approach allows researchers to integrate the findings of these fragmented studies into one comprehensive report.

To provide further assurance of the quality and objectivity of the study results, the systematic review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA 2020) guidelines. Additionally, because of the heterogeneity present in the study design, outcomes measured and context of each individual study, it was determined that conducting a meta-analysis would be impractical and therefore a structured narrative synthesis was applied. Narrative synthesis has been widely accepted as a means of synthesizing both qualitative and quantitative data related to behavioral and policy process issues (Popay et al., 2006; Snilstveit et al., 2012).

There were three main objectives of this study including:

(1) assessing the impact of water saving irrigation strategies on water productivity, crop yields and environmental impacts (RQ1);

(2) determining the socio-economic, behavioral and institutional factors affecting the rate at which small holder rice farmers adopt water saving irrigation technologies (RQ2); and

(3) evaluating how policies and governance arrangements affect the adoption of water saving irrigation technologies and the long term sustainability of the same (RQ3).

The time frame selected for the study (2015-2025) covers the most recent changes in agricultural policy in Malaysia and the effects of climate change and new technological innovations implemented since 2015. The geographic area of the study will cover MADA Regions I-III, and although all studies will be focused on rice systems in the state of Kedah, studies from similar rice growing areas of South East Asia may also be included to enable the comparison of different rice production systems and identify common themes of relevance to the development of policies to support the sustainable use of water resources in rice growing regions of Malaysia.

3.2 Search Strategy and Data Sources

A thorough search of peer reviewed articles and grey literature was conducted on academic databases that have been identified as being of most relevance to the subject matter. The primary databases used were; Scopus, Web of Science, Google Scholar and JSTOR, as they cover agricultural science, development studies and policy research. Additionally regional repositories such as MyJurnal (Malaysia) were also searched to include local knowledge and research.

The search terms were developed by combining four concept clusters:

1. Geography (Kedah, MADA, Malaysia);

2. Technologies related to irrigation (AWD, SRI, Precision irrigation, Water Saving);

3. Rice and small holder context;

4. Outcome or Policy aspects (Adoption, Water Productivity, Extension, Governance).

All searches were limited to English and Malay language publications.

Grey literature searches were made for Official Reports and Policy Documents from MADA, MAFFI, DID, DOSM, and International Organizations, i.e. FAO, IRRI and the World Bank. Manual screening of the reference lists of all included studies was completed using a "snow ball" method to identify further relevant literature.

3.3 Inclusion Criteria and Study Selection

Study selection used a modified version of the PICO framework (Population-Intervention-Comparator-Outcomes) (Higgins and Green, 2011). The study population focused on smallholder rice farmers that operated in irrigated lowland systems and generally had farm size less than 2 ha. The intervention included alternate wetting and drying (AWD), system of rice intensification (SRI), and precision micro/drip irrigation. Continuous flooding was the baseline comparison for these interventions.

Studies were selected based on the presence of quantitative results related to the interventions including but not limited to; water use, yield, adoption rate and economic impact of the interventions. Qualitative studies that reported on strong evidence regarding adoption barriers, institutional capacity and/or policy mechanisms that affected the adoption of the interventions were also included. Excluded from the review were commercial farms, other crop systems, rain-fed farming and any studies without adequate methodology.

A total of 1856 records resulted from an initial search using PRISMA procedures. After removing duplicates there were 1247 unique records. Following title/abstract screening, 235 full-text articles were assessed for eligibility and 85 studies were retained for synthesis. Two independent reviewers screened all of the records, with disagreements resolved through consensus.

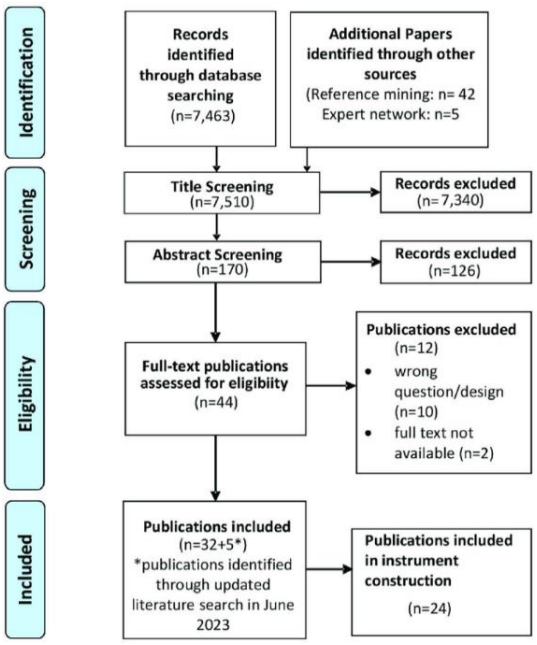

Figure 2: PRISMA 2020 Flow Diagram

3.4 Data Collection and Quality Assessment

The data were collected from all the studies included in this review using a standardized extraction form which recorded the study characteristics, the intervention details, the quantitative outcomes (such as water productivity, yield, adoption rate and economic benefits), and the qualitative findings (the barriers to adoption, gender dynamics, extension service capacity, and governance structures).

A quality assessment of the studies was conducted using the Mixed Methods Appraisal Tool (MMAT), allowing for a comparable assessment of all the different types of studies (qualitative, quantitative and mixed methods) (Hong et al., 2018). This resulted in the studies being classified into three categories (high, moderate and low quality) according to their methodological appropriateness, transparency and analytical rigour. Sensitivity analyses were also conducted to check whether the findings were influenced by lower quality studies.

3.5 Data Synthesis and Analytical Framework

Given the methodological and contextual diversity of the studies, a narrative synthesis (Popay et al., 2006) was used to synthesize the findings. The results of the studies were summarized for each type of technology and within each type of location, and thematic analysis (Ritchie and Spencer, 1994) was used to analyze the qualitative evidence.

Three analytical frameworks were used to interpret the findings. Firstly, the Technology Acceptance Model (TAM) was used to identify how farmers perceive the usefulness and ease of use of new technologies to inform their decision to adopt these (Davis, 1989). Secondly, the Diffusion of Innovations (DOI) framework was used to understand the attributes of the new technology which are likely to affect its uptake (Rogers, 2003). Finally, the Polycentric Governance Theory was used to identify how the institutional relationships between agencies and stakeholders affected the scale-up of new technologies (Ostrom, 2010). Triangulation among the quantitative findings, qualitative insights, and theoretical interpretations increased the validity of the analyses, and allowed for an integrated response to the research questions.

3.6 Limitations and Ethical Considerations

There are several limitations associated with conducting a secondary data review including the potential for publication bias, the limitation of available literature in certain languages, and the variation in contexts of the studies reviewed. However, there were numerous strategies implemented to increase the robustness of the study, such as systematic methodology, and a quality assessment process. There were no original data collections undertaken, therefore there was no requirement for obtaining ethical approval for this study. A protocol for this review was established before the initiation of the study, and documentation of this protocol has been completed to ensure that the review process is transparent and replicable.

4. Results and Discussion

As a secondary data-based study, this literature review has some constraints related to the nature of secondary data which include publication bias, language constraints, and variability in contexts of the individual studies examined. Despite these constraints, systematic processes and quality appraisal processes were used to increase the reliability of the study. Due to the fact that no primary data collection occurred, no ethics approval was needed for this research. The review protocol was developed before commencement of the literature search and documentation of the review process was completed in order to provide transparency and reproducibility.

4.1 Consolidated Summary of Results and Discussion

This systematic literature review examines the efficacy, adoption characteristics, and policy environment of water conserving irrigation techniques utilized in rice cultivation in the Kedah region of Malaysia's Muda Agricultural Development Authority (MADA) regions and other comparable environments in Asia. Overall, the results indicate that water conserving irrigation methods – specifically Alternate Wetting and Drying (AWD) and the System of Rice Intensification (SRI) – have shown to be technologically effective and environmentally sustainable and locally applicable. Despite the existence of significant body of evidence supporting their efficacy, however, the adoption of these approaches remains relatively low. The continuing disparity between demonstrated efficacy and low levels of adoption suggests that it is not technology per se that is the barrier to adoption, rather social, economic and institutional structures influencing farmers' decisions to adopt new technologies.

4.2 Effectiveness of Water Saving Irrigation Techniques

In general, water saving irrigation techniques have been shown to improve water productivity significantly when compared to traditional continuous flooding in all areas of Southeast Asia and comparable rice growing regions. AWD was found to be the most widely researched and operationally feasible method. Data suggest that AWD has resulted in an approximate 28% reduction in irrigation water usage (range = 24-35%) on average and in addition has produced a moderate increase in yield of 10-12% on average (Tuong and Bouman, 2003; IRRI, 2020). These increases in yield are believed to be due to increased oxygenation of roots during growth, lower loss of nutrients and more effective distribution of water throughout the crop life-cycle. Evidence collected at the local level in Kedah supports these regional findings. Between 2015 and 2024, pilot projects implemented through MADA in Region I and II (about 2500 ha) in Kedah reported water conservation and yields consistent with internationally established norms for AWD and confirmed its applicability in terms of soils, climate and existing irrigation infrastructure in Kedah (MADA, 2024). It should be noted that this local validation provides empirical evidence that the effectiveness of AWD in Kedah is based on actual experience and practice in Kedah's irrigation system, as opposed to being theoretically determined or imposed from outside the irrigation system.

Yield potential of SRI was generally higher than that of AWD in several reviewed studies. Reported increases in yields ranged from 20% to greater than 40% in studies where SRI performed well (Shamshiri, 2018; Lal, 2016). These increases in yield are associated with the wider spacing of plants, greater biological activity in the soil and improved cycling of nutrients. However, SRI exhibited greater variability in performance than AWD and this variability was attributed to differences in the skills of farmers, availability of labor and access to organic amendments. Precision irrigation technologies achieved the greatest water use efficiency - often greater than 40-50% water savings - but exhibited mixed yield responses and had limited scalability due to high capital costs, technical complexity, and soil compatibility issues (FAO, 2022).

Water-saving irrigation practices were found to produce significant environmental co-benefits beyond the improvements in productivity. The intermittent irrigation practices of AWD and SRI were found to reduce methane emissions by approximately 30-45% when compared to continuous flooding due to the reduced duration of prolonged anaerobic soil conditions (IPCC, 2019). Greater improvements in soil organic carbon and lower levels of nutrient leaching were observed in studies examining SRI and, to a lesser extent, AWD, thereby providing support for longer-term sustainability of the soils and environmental sustainability. Therefore, water-saving irrigation can be considered both a water resource management strategy and a meaningful climate mitigation and adaptation strategy.

4.3 Technical and Institutional Challenges in Smallholder Rice Systems in Kedah, Malaysia

Kedah and other developing countries' rice systems have the technical capability and need for water saving and efficient irrigated practices. Adoption of water-saving technologies has been very low. The evidence suggests there is a paradox between the technical effectiveness of water conserving technologies and the lack of adoption by small-scale rice producers; farmers who could be expected to adopt water conserving technologies. Farmers identify a number of factors as limiting their ability to adopt new water conserving irrigation techniques. They include:

a) Financial constraints - water conserving irrigation methods generally require some form of investment and ongoing maintenance/operation cost. Many small-scale rice farmers operate at marginal profit levels and/or under a heavy debt burden. When faced with the option of investing in new irrigation equipment, and given a number of competing demands for resources, many farmers will choose to invest in more immediate cash generating activities (e.g. fertilizers, pesticides etc.) rather than spending money on irrigation equipment.

b) Human capital and extension service availability – farmers with less formal education are less likely to have the skills required to understand and apply new irrigation techniques. Where new irrigation methods are seen as complicated, the likelihood of take-up by farmers with limited formal education decreases further. Additionally, the age profile of the farming community in Kedah makes it difficult to find younger farmers with the required skills and knowledge to train older farmers.

c) Risk perception – continuous flooding is seen by farmers in Kedah as a safe way to grow rice because they have grown rice in this way for generations. To stop the field from being flooded, even temporarily, contradicts the mental model of growing rice that farmers have developed over time. Regardless of empirical evidence, farmers perceive allowing the field to dry as a risk to the yield of the crop and therefore do not adopt water-conserving irrigation methods.

d) Gender inequity – although women contribute significantly to the labour component of rice production, women have limited access to extension services, credit, and formal decision making. Labour intensive water conserving methods (such as System of Rice Intensification (SRI))

place additional burdens on women's workload without providing adequate institutional support. As a result, the rate of adoption of water conserving irrigation methods in female headed household is consistently lower than male headed households, and represents both an equity issue and a lost opportunity for broader dissemination of water conserving irrigation methods.

4.4 Policy and Institutional Weaknesses

At a policy level, the failure to adopt water conserving irrigation technologies is exacerbated by the fragmented nature of institutions involved in agriculture, irrigation infrastructure, water allocations and environmental management. In Kedah, for example, these responsibilities are divided among several different departments/agencies with no overall coordination mechanism. As a result, there is a lack of alignment in objectives across departments/agencies. MAFI's primary focus is on achieving increases in food production and income for farmers, while DID is focused primarily on providing the necessary irrigation infrastructure and water supplies. MADA is responsible for implementing extension programs but does so in isolation from the integrated water resource management planning process undertaken by DOA. Finally, DOSM provides statistical information on agriculture but does not collect data systematically to provide feedback to policy makers. The net result is a "coordination vacuum".

As a result, there is no one agency that is accountable for water productivity outcomes. Therefore, no matter how effective the policy instruments used to achieve goals related to agriculture and food production may be, they will not effectively influence the behavior of farmers if those instruments do not provide them with a direct economic incentive to adopt water conserving irrigation practices. Evidence from Vietnam and India demonstrate that well-coordinated governance, effective extension services and targeted financial incentives can greatly improve the rate of adoption of water conserving irrigation practices, provided that the policies themselves are designed to directly address the constraints facing farmers.

4.5 Integrating Technical Effectiveness, Barriers to Adoption and Policy Responses

The integration of the effectiveness of water conserving irrigation practices, the barriers to their adoption and the characteristics of governance structures in Kedah reveal a logical link between the three areas. On the one hand, water conserving irrigation practices are effective in terms of reducing water usage while maintaining or improving yields and enhancing the resilience of rice cropping systems to drought and climate variability. On the other hand, despite their technical effectiveness, water conserving irrigation practices are not widely adopted by farmers in Kedah and elsewhere, largely due to the lack of economic incentives for doing so, as well as the limitations placed on farmers by financial constraints, limited extension capacity, risk aversion, gender inequality and institutional fragmentation. In order to overcome these constraints and realize the full benefits of water conserving irrigation practices, there needs to be a transition away from a technological approach to a policy approach that addresses the systemic barriers to adoption. Such a policy approach would involve integrating farmer support, institutional coordination, and inclusive design.

Technological adoption research has shown that whether or not farmers adopt new irrigation technologies, including water conserving ones, is not determined solely by the objective performance of the technology, but also by the perceived usefulness and ease of use of the technology, both of which are influenced by the social and economic context of the farmer (Davis, 1989). Diffusion research has shown that the lack of observability of the effects of new irrigation technologies (i.e. farmers cannot see or touch the technology), limited trialability of the technology (i.e. farmers cannot try out the technology before adopting it), and poor social learning networks (i.e. farmers do not know other farmers who have successfully implemented the technology) can all inhibit the adoption of new irrigation technologies, even when those technologies have clear advantages (Rogers, 2003). Governance research has also shown that poorly aligned sectoral policies can create perverse incentives for inefficient practices to continue, rather than promoting innovation (Ostrom, 2010).

4.6 Implications

In conclusion, the review demonstrates that water conserving irrigation strategies constitute a viable and empirically-supported solution to address the consequences of water scarcity, climate variability, and long term sustainability concerns in the rice sector of Kedah, Malaysia. Specifically, AWD represents a feasible and scalable option, offering significant reductions in water usage, stable or improved yields, and environmental co-benefits with low technical complexity. However, wide spread adoption of water conserving irrigation strategies will depend on changing the broader socio-economic and institutional context in which farmers make decisions. Coordinated governance, strengthened extension services, targeted financial support, and gender-inclusive program design are essential to translating proven effectiveness into sustained adoption and long-term impact.

5. Conclusion

Technical effectiveness and applicability of irrigation water saving technologies were demonstrated by the systematic review however; despite their apparent feasibility to meet the needs of smallholder rice farmers in Kedah's MADA region, water saving technologies have remained largely underutilized primarily due to socio-economic and institutional constraints rather than technological limitations.

The review has shown that both Alternate Wetting and Drying (AWD) and the System of Rice Intensification (SRI) consistently improve the water efficiency of irrigation while maintaining or improving crop yields. Water usage for irrigation with AWD is reduced by approximately one quarter when compared to conventional irrigation methods and also provides some improvement in yield and drought resilience in addition to the significant reduction in water used for irrigation. While SRI may potentially provide higher yields and contribute to long term soil health via increased levels of organic carbon and nutrients available to plants and microorganisms, it has also been shown to provide significant environmental co-benefits including reductions in methane emission and improved soil quality. In addition to demonstrating the technical feasibility of these two water saving irrigation methods in Kedah's agro-ecological and infrastructural environment, the review also shows that the benefits they offer are realizable in practical terms using the same conditions found in the MADA pilot areas.

The review identified an ongoing effectiveness-adoption paradox; despite the fact that the technologies being reviewed had strong technical performance, there was little uptake of the technologies by farmers especially those who were considered to be the most vulnerable. The reason for this lack of adoption was the result of structural barriers which included, but were not limited to, limited access to initial capital required to acquire the technologies, poor coverage of extension services, high risk aversion of households constrained by debt, poor communication and information exchange between farmers, and inequitable distribution of resources and decision making authority based on gender. These structural barriers limited farmers' ability to transform the proven technical advantages of the technologies into practical applications even if farmers were aware of the technologies.

The review has demonstrated that the effect of these structural barriers to technology adoption can be overcome through policies that provide a systemic approach to supporting the development of water-saving irrigation systems in smallholder rice producing systems. The review cited comparative evidence from several other Asian countries that showed how coordinated government efforts combined with adequate financial support for farmers, and improved extension services supported by inclusive programming approaches could dramatically increase the rate of technology adoption at scale. Therefore, the major challenge facing Kedah in developing water-saving irrigation systems for its smallholder rice producers is to create integrated and systemic institutional arrangements and support mechanisms that are responsive to the needs of farmers and supportive of achieving the goals of agriculture, water management, and climate mitigation and adaptation.

In summary, the review has clearly demonstrated that the challenges associated with developing and implementing large-scale water-saving irrigation systems for smallholder rice producers in Kedah are largely political and social challenges that require the creation of new institutions and policies rather than technical ones. To achieve widespread adoption of water-saving irrigation systems for smallholder rice producers in Kedah requires an integrated approach to addressing the financial, institutional, extension, risk, and gender-related barriers to the adoption of proven technologies. With growing water scarcity and climate variability, timely policy actions are needed to ensure the continued sustainability of rice production and smallholder livelihoods in Kedah and similar regions.

Acknowledgements

The authors gratefully acknowledge Albukhary International University (AIU), School of Business and Social Sciences, Alor Setar, Kedah, Malaysia, for providing library access, research facilities, and institutional support that enabled this systematic review. Special thanks go to colleagues who offered valuable feedback on drafts and to MADA and DID for gray literature resources.

Conflict of Interest Statement

The authors declare that this research was conducted without any commercial or financial conflicts and affirm no conflicting interests with funders or institutions. One author serves as the postgraduate supervisor of the other, with contributions delineated below to ensure transparency.

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