HI-AWARE Working Paper 14

# Water Management Technologies for Climate Smart Agriculture in South Asia

## A Review

Consortium members

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This series is based on the work of the Himalayan Adaptation, Water and Resilience (HI-AWARE) consortium under the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA) with financial support from the UK Government's Department for International Development and the International Development Research Centre, Ottawa, Canada. CARIAA aims to build the resilience of vulnerable populations and their livelihoods in three climate change hot spots in Africa and Asia. The programme supports collaborative research to inform adaptation policy and practice.

HI-AWARE aims to enhance the adaptive capacities and climate resilience of the poor and vulnerable women, men, and children living in the mountains and flood plains of the Indus, Ganges, and Brahmaputra river basins. It seeks to do this through the development of robust evidence to inform people-centred and gender-inclusive climate change adaptation policies and practices for improving livelihoods.

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Feedback is welcomed as a means to strengthen these works: some may later be revised for peer-reviewed publication.

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## A Review

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# Contents

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# Acronym and Abbreviations

| | |
|---|---|
| AWM | Agriculture Water Management |
| AGORA | Access to Global Online Resources in Agriculture |
| DMI | Drip Method of Irrigation |
| CSA | Climate Smart Agriculture |
| CMI | Conventional Method of Irrigation |
| FAO | Food and Agriculture Organisation of the United Nations |
| GHG | Green House Gas |
| MI | Micro-Irrigation |
| MIS | Micro-irrigation Systems |
| NA | Not Applicable |
| NGOs | Non-governmental Organisations |
| CT | Conventional Tillage |
| CAW | Conservation Agriculture-based Wheat Production System |
| CTW | Conventional Tillage-based Wheat Production System |
| EEA | European Environment Agency |
| SALT | Sloping Agricultural Land Technology |
| RCT | Randomized Control Trial |
| RWC | Rice-Wheat Consortium of the Indo-Gangetic Plains |
| SPIPs | Solar Powered Irrigation Pumps (SPIPs) |
| USD | United States Dollars |
| WUE | Water Use Efficiency |
| UNEP | United Nations Environment Programme |
| ZR | Zero Tillate |
| ADB | Asian Development Bank |
| BCAS | Bangladesh Center For Advance Studies |
| CARIAA | Collaborative Adaptation Research Initiative in Africa and Asia |
| CAEWRI-PARC | Climate, Energy & Water Research Institute - Pakistan Agricultural Research Council |
| HI-AWARE | Himalayan Adaptation, Water and Resilience Research |
| ICIMOD | International Centre for Integrated Mountain Research Development |
| IDRC | International Development Research Centre |
| TERI | The Energy and Resources Institute |
| IWMI | International Water Management Institute |

# Abstract

The purpose of the paper was to review selected agricultural water management technologies positioned as climate smart agriculture (CSA), in South Asia. Using the Delphi process, we shortlisted three technologies for the review: zero tillage (ZT), solar-powered irrigation pumps (SPIPs), and micro-irrigation (MI). The technologies were then evaluated on their climate smart aspects. Our analysis found that introduction of climate smart technologies leads to a rise in productivity, water, and energy savings at field level. If we extend the analysis from the field to the basin level, we observe that widespread adoption of such technologies may increase water and energy consumption, thereby offsetting the initial efficiency gains of climate smart technologies. We also found a lack of rigorous impact assessment of these technologies, indicating scope for more internally valid evaluation methodologies.

# 1. Introduction

Agriculture is vital to South Asia's growth prospects, as about 70% of the population live in the rural areas. Most of the rural poor depend primarily on agriculture for their livelihoods (IFAD, 2007). A 2014 Asian Development Bank (ADB) report that measures the costs of climate change and adaptation in South Asia states that agriculture in the region has improved in recent years, with more people being fed (Ahmed et al., 2014). However, agriculture in the region is extremely susceptible to climate change, mostly in the form of change in intensity of rainfall events, and the break cycles of monsoon combined with increased risk of critical temperatures being experienced at more frequent intervals. In fact, as reported by the International Fund for Agricultural Development (IFAD), temporal and special changes in temperature coupled with water stress will have key implications for agriculture, and will in particular adversely impact crop yields. For instance, models project a 15%–30% decline in the productivity of most cereals. Rice, a staple cereal across the region, will face a decline of 0.75 tonnes/ha in yield for an increase in temperature of 2–4 °C associated with climate change. Overall, the report points to a crop yield decrease of 30% in the region by the mid-21st century, with the most dramatic negative impacts expected in arid zones and flood-affected areas. Further projections also state that irrigation demand for agriculture in arid and semi-arid regions is likely to increase by 10% for a temperature increase of 1% (IFAD, 2007). Considering these negative impacts of climate change on agriculture, a sustainable approach to adapt to climate change is crucial. A 'climate smart agriculture' (CSA) initiative was proposed to sustainably cope with the negative effects of climate change.

The CSA approach is intended to support actions required to change and reorient agricultural systems to ensure food security and so combat climate change. This approach has three main objectives: (1) to sustainably increase agricultural productivity and incomes; (2) to adopt and build resilience to climate change; and (3) to mitigate greenhouse gas (GHG) emissions (FAO, 2016). The concept of CSA was developed by the Food and Agriculture Organization (FAO) as a unified approach to address climate change challenges. The initiative was formally launched in 2010 in a background paper prepared for the Hague Conference on Agriculture, Food Security and Climate Change (FAO 2010). An important take-home message from the paper is to make production systems more resilient; that is, improving the capability of performing well in the face of disruptive events in order to safeguard output and income. The paper also states that more resilient and productive agriculture requires alterations in the way natural resources are managed (e.g., land, water, soil nutrients, and genetic resources) and greater productivity in the use of these resources and inputs for production. The overall efficiency, capacity to adapt, resilience, and mitigation possibilities of the production systems can be strengthened through improving their various components. The key components are soil and nutrient management, water harvesting and use, pest and disease control, resilient ecosystems, genetic resources, as well as harvesting, processing, and supply chains (FAO, 2010).

In combating the effects of climate change, and to support CSA, the advent of agriculture water management (AWM) techniques, which improve water harvesting and use, have been particularly effective. AWM can be referred to as a planned development, distribution, and use of water resources to meet predetermined agricultural objectives. It is an overarching term that includes soil and water conservation and irrigation management (IFAD, 2012). In essence, efficient management of water for agriculture tends to address climate change by targeting the root of the problem: access to water. AWM techniques are significant as using them helps to achieve the climate smart goals of sustainably increasing agricultural productivity, enhancing resilience through efficient water use, removing GHGs, and enhancing food security.

The purpose of this review paper is, therefore, to identify and review the AWM technologies that are climate smart. We prepared a comprehensive list of technologies that were identified as climate smart. The list was then narrowed down through consultations with experts using the Delphi methodology. Following the methodology, we shortlisted micro-irrigation (MI), solar-powered irrigation pumps (SPIPs), and zero tillage (ZT) through this process. The technologies were then evaluated on their climate smart aspects, in terms of whether they enhanced agricultural productivity; improved water savings and productivity; and are energy saving. On average, we found there was a rise in yield, water productivity, and energy savings for field-level studies associated with these technologies. The improvement in water savings from their adoption could lead to an increase in irrigated area, higher input use and, subsequently, greater energy consumption. This means that an increased adoption of AWM technologies might lead to higher usage of water and energy at basin level. This behaviour fits into the paradox of irrigation scheme modernization literature, discussed in detail in section 8. Other than the climate smart aspects of the three technologies, our review found several case studies which highlight the technologies to be effective coping tools for climate change.

# 2. Methodology

## 2.1. Delphi Process

At the outset, we prepared a comprehensive list of AWM technologies for the Delphi process. A modified version of the Delphi process was followed, enabling a continuously iterated process of discussions until a consensus was determined through a survey process. This was carried out in four rounds:

1. An open-ended discussion was held with key informants (experts) to generate a preliminary list of CSA water management technologies (Appendix 1).
2. A list of climate smart technologies was sent to key experts to shorten the list to 10 technologies to establish preliminary priorities among the existing technologies. This process was done through update meetings and email correspondence.
3. Each Delphi panelist received a short questionnaire administered through SurveyMonkey. The questionnaire contained questions relating to rating 10 AWM technologies under three criteria: water saving, energy saving, and agricultural productivity.
4. The results of the survey in the form of ratings consensus was disseminated to the panellists. This allowed them to revise or provide feedback on the ratings.

## 2.2. SurveyMonkey Survey Process

A SurveyMonkey questionnaire was sent to 47 experts in the field as part of Round 3 of the Delphi process. The number of experts was initially 36 but increased after subsequent additions to the list. Email invitations were sent to the individuals on the list, and a regular follow-up was conducted to elicit responses to the survey, through group and individually drafted emails.

A subsequent follow-up was carried out by sending a website link as a gentle reminder. We were able to obtain 19 responses of the possible 47 that were requested (approximately 40% responded).

## 2.3. Results from SurveyMonkey

The ranking of AWM technologies derive from the 19 responses we received. On a Likert scale of 1 (the lowest) to 6 (the highest), the experts were asked to rate the technologies on the criteria of water saving, energy saving for agricultural purposes, and agricultural productivity gains. These scores were then processed to obtain the weighted average scores for each technology. The criteria were:

- Water saving: MI, checking dams for runoff collection, conservation ponds, and conservation tillage were highly rated. The top five technologies following this criterion were MI, conservation ponds, checking dams, conservation tillage, and cover crops.
- Agricultural productivity gains: MI, systems of rice intensification, and cover crops were highly rated. The top five technologies following this criterion were MI, systems of rice intensification, cover crops, SPIP, and conservation tillage.
- Energy saving: SPIPs and conservation tillage were highly rated. The top three technologies following this criterion were MI, SPIPs, and conservation tillage.

After considering the average score received for each of the technologies, we listed the top three according to rank: conservation tillage, SPIPs, and MI. Among conservation tillage technologies we chose ZT as it had the highest rate of adoption in the Indo-Gangetic Plains (IGP). MI, SPIPs, and ZT were finally shortlisted for the literature review.

The majority of the respondents (78.9%) felt that the review should be conducted in a South Asian context, rather than in a global context.

Appendix 2 contains detailed scores for each of the technologies.

## 2.4. Inclusion/Exclusion Criteria

Once the technologies were identified, we devised inclusion/exclusion criteria for shortlisting studies of interest. A high proportion of our experts wanted the review to be for South Asia and so we excluded articles for other regions in the world. Since CSA is a relatively new concept (FAO, 2010), we looked at studies post-2000. This makes our review pertinent within the climate change literature. We reviewed studies on the three technologies in South Asia including published studies in journals, unpublished articles, and book chapters. A major source for our literature search was the Access to Global Online Research in Agriculture (AGORA) database which is administered by the Food and Agriculture Organization (FAO). We excluded articles that were technical in nature (i.e., published for engineering or natural sciences audiences). We identified 53 studies pertaining to MI, SPIP, and ZT technologies. Each is reviewed in the following sections.

# 3. Micro-irrigation (MI)

## 3.1. Background

MI comprises a family of irrigation systems that emit water through small devices. The devices usually deliver water onto the surface of the soil very close to the plant, or below the surface of soil directly to the root (Hla et al., 2003). MI systems predominate in arid and semi-arid regions where problems of water scarcity are extensive. In irrigated agriculture, they are used mostly for row crops, mulched crops, orchards, gardens, greenhouses, and nurseries. Emission devices deliver water in three different modes: drip, bubbler, or micro-sprinkler. In drip mode, water is emitted in droplets and trickles. In bubbler mode, the water bubbles out from the device. In the case of the micro-sprinkler, the water is sprinkled, sprayed, or misted (Hla et al., 2003).

MI technologies have often been associated with capital-intensive, commercial farms with wealthier farmers, being unaffordable for small-scale farmers. However, with the recent technical transformations from largely capital-intensive features to input mode i.e. technologies with lower input costs, it has become widely affordable and applicable in sizes suitable for smaller plots. The drip method tend to be more readily adopted in agriculture than bubblers or micro-sprinklers (Namara et al., 2005). The advent of cheaper drip systems such as Pepsee systems, for which initial investment is 41% less than that for micro-tubes and 78% less than conventional drip systems, has led to their to wider adoption (Verma, 2004).

- A review of literature related to MI technologies shows that they are promoted or adopted for one or more of the following objectives (Namara et al., 2005):
    - As a means of saving water in irrigated agriculture and coping with the water crisis.
    - As a strategy to increase income and use it for poverty alleviation among rural communities through increasing crop yield.
    - To enhance food and nutritional security in rural households.
    - As a means to extend the limited available water over a larger cropping area during water-scarce periods.

In the context of our review, we focused on the use of these devices in irrigation, emphasizing AWM that is climate smart. In other words, we analysed the literature on MI to judge if the devices were yield enhancing, water saving, and energy saving as compared to the traditional methods of irrigation practised. The review also delves into the differences between the sample farm-level observations and experimental plot level observations to look into the extent of savings achieved.

## 3.2. Studies

After applying the inclusion/exclusion criteria, about 22 studies were identified and reviewed. The studies were classified according to the type of method used when collecting data and the nature of the study.

Three categories were used to distinguish the method used in the sites:

- On-station trials (controlled environments in research institutes).
- On-farm trials (controlled environments in farmers' fields).
- Actual implementation (in farmers' fields).

Table 1: **Studies of micro-irrigation**

| Authors | Country | Experimental | Data collection method |
|---|---|---|---|
| Narayanamoorthy. A. (2004) | India (Maharastra) | No | Actual implementation |
| Malunjkar et al. (2015) | India (Maharastra) | Yes | On-station trial and on-farm trial |
| Surendran et al. (2016) | India (Tamil Nadu) | Yes | On-station trial |
| Kumar et al. (2009) | India (Uttarakhand) | Yes | On-station trial |
| Verma (2004) | India | No | Actual implementation |
| Verma et al. (2004b) | India (Madhya Pradesh and Maharastra) | No | Actual implementation |
| Verma et al. (2004a) | India (Madhya Pradesh) | No | Actual implementation |
| Namara et al. (2007) | India (Gujrat and Maharastra) | No | Actual implementation |
| Qin et al. (2016) | China (Gansu Province) | Yes | On-station trial |
| Narayanamoorthy (2005) | India (Tamil Nadu) | No | Actual implementation |
| Randev (2015) | India (Himachal Pradesh) | No | Actual implementation |
| Von Westarp et al. (2004) | Nepal (Panchkhal Horticulture Farm) | Yes | On-station trial |
| Kumar et al. (2008) | India | No | Actual implementation |
| Sakthivadivel et al. (2004) | India | No | Actual implementation |
| Narayanamoorthy (2007) | India (Hyderabad) | No | Actual implementation |
| Vishwanathan et al. (Narayanmoorthy) (2016) | India (Maharastra) | No | Actual implementation |
| Vishwanathan et al. (2016) | India (Gujarat) | No | Actual implementation |
| Vishwanathan et al. (Dinesh Kumar) (2016) | India (Rajasthan) | No | Actual implementation |
| Vishwanathan et al. (D. Suresh Kumar) (2016) | India (Tamil Nadu) | No | Actual implementation |
| Vishwanathan et al. (Chandra S. Bahinipati et al.) (2016) | India (Gujarat) | No | Actual implementation |
| Chandran et al. (2016) | India (Kerala) | No | Actual implementation |
| Kumar et al. (2004) | India (Gujrat) | No | Actual implementation |

In the subsequent sections we present a review of the yield-enhancing, water-saving, and energy-saving aspects of MI technologies that make them climate smart.

## 3.3 Agricultural Productivity Gains

Yield gains or productivity gains are a direct result of an increase in production as a result of provision of efficient conditions for the crops to grow. Among the conditions, irrigation is integral to the growth process. Hence, many of the productivity gains achieved can be attributed to the use of an efficient irrigation system.

Of the MI devices, the drip method of irrigation (DMI) is seen to be the most efficient in terms of economic and productive viability. The higher yields are the result of three factors (Narayanamoorthy, 2005):

- There is less moisture stress and so growth is very good.
- Weed growth is comparatively less because water is supplied directly to the root zone.
- Since fertilizers are administered through water (fertigation), they are provided efficiently by limiting losses occurring through evaporation and leaching with water.

In addition to these, the ability to prepone a crop under DMI results in significant gains as it leads to higher yields that translate into higher incomes. For instance, cotton farmers in Maikaal were able to take advantage of pre-monsoon cotton, allowing them to prepone the wheat crop. Preponing the cotton sowing by 30–40 days leads to an increase in harvest and subsequently an increase in yield (Sakthivadivel at el., 2004).

Our literature review, which focused on recent studies (i.e., 2000 onwards), pointed to a varying degree of yield gains depending in large part on the type of crops grown. As a result of MI technology adoption, the yield gains were observed to be from as low as 4% to as high as 121%. It is important to note the essence of what the percentage increase means in the case of each crop under consideration. For instance, it was found that the yield gains for horticultural crops and orchards such as banana, grapes, orange, coconut, and sugarcane translate into a significant rise in the value of crop output, even if there was only a marginal increase in yield. This can be seen to be a result of the high value of these crops, and can be illustrated by looking at cereal and pomegranate crops. A 10% rise in yield would result in an incremental gain of 400–500 kg wheat or INR 3,000–3,750 per hectare of irrigated wheat. A 10% increase in yield of pomegranate, with minimum yield of 60,000 kg per hectare per year, would result in an incremental gain of 6,000 kg per hectare or INR 90,000 per hectare (Kumar et al., 2008).

However, a study conducted in Rajasthan, India, points out that not all MI devices may offer favourable results in terms of yield gains. In this case the adoption of a sprinkler system did not lead to a substantial change in yield. A notable decrease in the yield of wheat, a marginal decrease in yield in groundnut and cluster bean, and only a slight increase in yield of pearl millet (*bajra*) has been observed. This yield reduction can be attributed to poor distribution uniformity in watering, which have adverse effects on crop growth (Viswanathan et al., 2016).

Regardless of whether the studies made use of an experimental plot or sample farmers in actual field situations, most studies reported yield gains as a result of adopting the MI system as compared to traditional method of irrigation. Table 2 provides a synopsis of yield gains reported in each of the studies reviewed.

Table 2: **Yield change for micro-irrigation**

| Authors | Country | Increase in yield | Percentage change |
|---|---|---|---|
| Narayanamoorthy (2007) | India (Maharastra) | Yes | Productivity gains of 29%, 19%, and 23% observed in banana, grapes, and sugarcane, respectively, as a result of the use of DMI over FMI |
| Malunjkar et al. (2015) | India (Maharastra) | Yes | Banana yield gain of 22% and 28% observed in experimental site and farmer's field, respectively, as a result of use of DMI over CMI |
| Surendran et al. (2016) | India (Tamil Nadu) | Yes | Average agricultural yield gain of 17% as per the use of LCDI over FMI |
| Narayanamoorthy (2004) | India (Maharastra) | Yes | Productivity gain of 23% observed as a result of the use of DMI over FMI |
| Kumar et al. (2009) | India (Uttarakhand) | No | Yield not significantly different between gravity-fed MIS and checking the basin irrigation system |
| Verma (2004) | India | N/A | |
| Verma et al. (2004b) | India (Madhya Pradesh and Maharastra) | N/A | N/A |

| | | | |
|---|---|---|---|
| Verma et al. (2004a) | India (Madhya Pradesh) | Yes | N/A |
| Namara et al. (2007) | India | Yes | In banana, groundnut, and cotton the use of MI technologies generally resulted in significant yield improvement over traditional irrigation practices |
| Qin et al. (2016) | China (Gansu Province) | Yes | The biomass of maize under drip irrigation was higher than under border irrigation by an average of 42% in 2014 and 26% in 2015. The maize gained more water and nutrition leading to higher yield in a shorter time. |
| Narayanamoorthy (2005) | India (Tamil Nadu) | Yes | Sample farmer reported productivity gains of about 55% for sugarcane as compared to FMI |
| Randev (2015) | India (Himachal Pradesh) | Yes | Respondents also observed that apple yield was enhanced by 35% after adoption of drip-irrigation system |
| Von Westarp et al. (2004) | Nepal (Panchkhal Horticulture Farm) | Yes | Yield gain of about 12% from the use of low-cost drip-irrigation system was observed over hand watering (and needed only 50% of the former water requirement for the crop) |
| Kumar et al. (2008) | India | Yes | Literature review showed that drip-irrigation increased yield from 5% to as high as 50% |
| Sakthivadivel et al. (2004) | India | Yes | Use of drip irrigation enabled farmers to prepone cotton sowing by 30–40 days, harnessing the benefits of pre-monsoon cotton and then preponing the wheat crop; translated into higher wheat yield |
| Vishwanathan et al (Narayanamoorthy) (2016) | India (Maharastra) | Yes | 114% gain in yield (productivity) observed in cotton for DMI over FMI. |
| Vishwanathan et al. (2016) | India (Gujarat) | Yes | Crop yield increases reported to be quite significant, from as high as 121% for fennel during kharif to 80% in groundnut in summer, and to 56% for castor during kharif (rainy season) to 32% in wheat during rabi (winter) |
| Vishwanathan et al. (Dinesh Kumar) (2016) | India (Rajasthan) | Yes | Yield of groundnut and cluster bean decreased marginally; yield of pearl millet (*bajra*) increased marginally. Overall, no general trend in yield. One limitation may be that only monsoon and winter seasons were observed |
| Vishwanathan et al. (D. Suresh Kumar) (2016) | India (Tamil Nadu) | Yes | Yield increase observed in banana, coconut, grapes, and turmeric in the region of 4%, 15%, 16%, and 22%, respectively |
| Vishwanathan et al. (Chandra Sekhar Bahinipati et al.) (2016) | India (Gujarat) | Yes | 83% of respondents perceived that adoption of MIS resulted in yield increase |
| Chandran et al. (2016) | India (Kerala) | Yes | Yield increase observed in coconut, arecanut, and nutmeg in the region of 19%, 13%, and 47%, respectively |
| Kumar et al. (2004) | India (Gujrat) | Yes | Alfalfa yield enhancement through use of drip system ranged from 7.4% to 10.8% |

CMI, conventional method of irrigation ; DMI, drip method of irrigation; FMI, flood method of irrigation ; LCDI, low cost drip irrigation; MIS, micro-irrigation systems; NA, Not applicable.

## 3.4. Water Saving and Productivity

Water saving or improving the physical productivity of water used in irrigated agriculture are synonymous for the purpose of this review. The water-saving potential of the MI technologies can be acquired in two ways. This concept can be explained as 'dry' water saving and 'wet' water saving. Dry water saving refers to reducing the water consumption for a particular crop. Wet water saving is achieved when the yield of a crop is enhanced without changing the amount of water consumed (Kumar et al., 2008). Both types of water saving can be observed as a result of the adoption of MI systems. However, it is vital to note that wet water saving, or 'real water saving', is more significant when it comes to semi-arid and arid regions. The application of MI systems in these regions seem to be more prevalent for their real water saving capabilities.

The review of literature consisting of recent studies (i.e., 2000 onwards) shows water saving in the range of 25%–80%. A few studies discuss improvements in water use efficiency (WUE) when dealing with the water saving achieved. It is essential to understand that the real water saving from these systems depend largely on enhancements in WUE at the field level. (Kumar et al., 2008). However, most of the studies reviewed base their results primarily on dry water saving (applied water) rather than on wet water saving. Hence, it is essential to look into these distinctions when reviewing the extent of savings presented.

The fluctuations in the extent of water saving are primarily due to the different types of crops involved in each of these studies. It is also useful to note that comparison of MI systems with the traditional method of irrigation systems could be the varying factor. The condition of the traditional methods of irrigation systems used for comparison would be crucial. Comparing a poorly managed irrigation system with an MI system would lead to much higher and more significant water savings as opposed to other well-managed ones (Kumar et al., 2008).

In terms of water saving at the holistic level in the context of both experimental plots and sample farmer-owned plots, MI systems make a large contribution to net water savings. This comes in the form of substantial reductions in losses due to deep percolation, evaporation, and inefficient field conveyance and distribution systems (Namara et al., 2007). A brief synopsis of the water savings reported in each of the studies reviewed appears in Table 3.

Table 3: **Water savings for micro-irrigation**

| Authors | Country | Saving | Percentage change |
|---|---|---|---|
| Narayanamoorthy (2007) | India (Maharastra) | Yes | Water savings of 44%, 37%, and 29% observed in sugarcane, grapes, and banana, respectively, from use of DMI over FMI |
| Malunjkar et al. (2015) | India (Maharastra) | Yes | Water savings of 35% and 29% in experimental site and farmer's field, respectively, from use of DMI over CMI |
| Surendran et al. (2016) | India (Tamil Nadu) | Yes | Water saving of 45% observed in sugarcane as a result of LCDI over FMI |
| Narayanamoorthy (2004) | India (Maharastra) | Yes | Water saving of about 44% per hectare as a result of DMI over FMI |
| Kumar et al. (2009) | India (Uttarakhand) | Yes | Water savings of 41% and 33% observed in garden pea and French bean, respectively, from use of gravity-fed MIS |
| Verma (2004) | India | Yes | Review states that most studies point to farm-level savings in water that might actually only be notional savings |
| Verma et al. (2004b) | India | Yes | Observations at Maikaal suggest that adoption of MI technologies leads to improved water efficiency at the individual farm level, but unless the technologies are adopted on a large scale, the impact would not be significant at the basin level |
| Verma et al. (2004a) | India (Madhya Pradesh) | Yes | Notional saving of 50% of water used |

| | | | |
|---|---|---|---|
| Namara et al. (2007) | India | Yes | Study highlights that water application can be reduced by 50%–100% through use of drip irrigation |
| Qin et al. (2016) | China (Gansu Province) | Yes | Water savings as a result of shorter growth days as compared to border irrigation. Growth days shortened by nearly 0.5 month in 2 years |
| Narayanamoorthy (2005) | India (Tamil Nadu) | Yes | Adopting drip irrigation from each acre (about 0.4 hectare) of sugarcane can save over 58% water |
| Randev (2015) | India (Himachal Pradesh) | Yes | 25% water saving observed by drip-irrigation users surveyed in Himachal Pradesh (130 respondents from Shimla District) |
| Von Westarp et al. (2004) | Nepal (Panchkhal Horticulture Farm) | Yes | Water saving, in terms of scarce water allocation, seen to be efficient compared to conventional irrigation |
| Kumar et al. (2008) | India | Yes | Literature review shows that drip irrigation leads to substantial savings in applied water over conventional irrigation |
| Sakthivadivel et al. (2004) | India | Yes | 80% water saving observed from use of drip irrigation over furrow irrigation |
| Vishwanathan et al (Narayanamoorthy) (2016) | India (Maharastra) | Yes | Water saving for sugarcane, grapes, and banana similar to another study published on the same (Narayanmoorthy 2007).Water saving in cotton observed to be 45% (in terms of savings in applied water) |
| Vishwanathan et al. (2016) | India (Gujarat) | Yes | 30% overall water savings observed under MI; 64% in summer when water is most scarce |
| Vishwanathan et al. (Dinesh Kumar) (2016) | India (Rajasthan) | Yes | 39% water saving observed from adoption of sprinkler irrigation. Every hectare sprinkler-irrigated saved 816 $m^3$ water |
| Vishwanathan et al. (D. Suresh Kumar) (2016) | India (Tamil Nadu) | Yes | Water saving is valued at INR 149,393 per hectare in the over-exploited regions; INR 76,943 per hectare in semi-critical region |
| Vishwanathan et al. (Chandra Sekhar Bahinipati et al.) (2016) | India (Gujarat) | Yes | Of 355 farmers interviewed randomly, over 88% of respondents perceived and responded that MIS saved water |
| Chandran et al. (2016) | India (Kerala) | Yes | No savings in water is specifically mentioned. However, DMI is used to cope with water scarcity. |
| Kumar et al. (2004) | India (Gujrat) | Yes | Water saving through drip system ranged from 7.2% to 43% |

CMI, conventional method of irrigation ; DMI, drip method of irrigation; FMI, flood method of irrigation ; LCDI, low cost drip irrigation; MIS, micro irrigation systems; NA, Not applicable.

## 3.5. Energy Savings

Energy savings as a result of adopting MI systems relate mostly to reduction in working hours of the pump sets, as a direct result of reduction in water consumption. In the context of this review, energy savings have mostly been characterized as electricity savings, in line with the bulk of the observations in the reviewed studies.

The literature review shows that electricity savings from the adoption of MI systems fall in the range of 25%–77%. The wide variation in savings is observed to be a result of different field conditions and the unit of observations in the studies reviewed. For instance, in hard rock areas such as Maharashtra, Madhya Pradesh, Tamil Nadu, Karnataka, and Andhra Pradesh, farmers cannot pump as much water. They usually have to discontinue pumping after 2–3 hours of pump use and use water sparingly. Adoption of MI systems in this case might translate to more efficient use of the pump by reducing the rate at which the water is pumped (Kumar et al., 2008). Hence, the degree of savings as a result of adoption of MI systems depends on the condition of the field areas under consideration. Variation in savings can also occur as a result of the different unit of observations used. For example, a sample farmer from Tamil Nadu reported savings of 1,260 kwh (58%) for each acre (about 0.4 hectare) of sugarcane cultivation. An observation of sugarcane farmers in Maharashtra shows savings of 1,059 kwh (44.43%) per hectare in sugarcane cultivation. Reported savings can fluctuate when different units – like acre and hectare in the above case – are used.

We observed that more efficient use of pumps for irrigation results in significant energy cost reduction (electricity costs) for both experimental and sample farmer fields. Table 4 provides a synopsis of energy savings in each of the studies reviewed.

Table 4: **Energy savings for micro-irrigation**

| Author | Country | Saving | Percentage change |
|---|---|---|---|
| Narayanamoorthy (2007) | India (Maharastra) | Yes | Electricity savings of 44%, 37%, and 29% observed in sugarcane, grapes, and banana, respectively, from use of DMI over FMI |
| Malunjkar et al. (2015) | India (Maharastra) | Yes | Electricity savings of 38% and 33% in experimental site and farmer's field, respectively, from use of DMI over CMI |
| Surendran et al. (2016) | India (Tamil Nadu) | Yes | Average electricity saving of 25% from the use of LCDI over FMI |
| Narayanamoorthy (2004) | India (Maharastra) | Yes | Electricity saving of 44% observed from use of DMI over FMI |
| Kumar et al. (2009) | India (Uttarakhand) | N/A | |
| Verma (2004) | India | N/A | |
| Verma et al. (2004b) | India (Madhya Pradesh and Maharastra) | N/A | |
| Verma et al. (2004a) | India (Madhya Pradesh) | Yes | Adoption of Pepsee systems seen to decrease total hours of pumping, leading to energy savings. Pepsee systems have led to greater pumping of water in some cases as they helped farmers to obtain a summer crop of cotton, which was not possible earlier |
| Namara et al. (2007) | India | N/A | |
| Qin et al. (2016) | China (Gansu Province) | N/A | |
| Narayanamoorthy (2005) | India (Tamil Nadu) | Yes | Estimated saving of around 58% electricity from each acre (about 0.4 hectare) of sugarcane cultivation by adopting drip method |
| Randev (2015) | India (Himachal Pradesh) | N/A | |
| Von Westarp et al. (2004) | Nepal (Panchkhal Horticulture Farm) | N/A | |
| Kumar et al. (2008) | India | N/A | |
| Sakthivadivel et al. (2004) | India | Yes | Total number of hours pumping required for the whole season significantly less for drip irrigation compared to furrow irrigation. This saving in electricity can be used to grow much more by irrigating additional land. |

| | | | |
|---|---|---|---|
| Vishwanathan et al (Narayanamoorthy) (2016) | India (Maharastra) | Yes | An increase in electricity consumption by 45% is observed for cotton for DMI over FMI. |
| Vishwanathan et al. (2016) | India (Gujarat) | N/A | |
| Vishwanathan et al. (Dinesh Kumar) (2016) | India (Rajasthan) | N/A | |
| Vishwanathan et al. (D. Suresh Kumar) (2016) | India (Tamil Nadu) | Yes | Per hectare electricity saving in the over-exploited region observed to be 73%. In semi-critical region, electricity saving observed to be 77% per hectare |
| Vishwanathan et al. (Chandra Sekhar Bahinipati et al.) (2016) | India (Gujarat) | Yes | Of 355 farmers interviewed randomly, 63% of respondents perceived and responded that MIS saved energy. |
| Chandran et al. (2016) | India (Kerala) | N/A | |
| Kumar et al. (2004) | India (Gujrat) | Yes | Energy savings ranged from 31 kwh per year to 232 kwh per year as observed from four plots |

CMI, conventional method of irrigation ; DMI, drip method of irrigation; FMI, flood method of irrigation ; LCDI, low cost drip irrigation; MIS, micro irrigation systems; NA, Not applicable.

# 4. Solar-powered Irrigation Pumps (SPIPs)

## 4.1. Background

The SPIP is a clean technology to lift water and provide irrigation facilities to farmers. SPIP technology offers a wide range of benefits:

- SPIPs do not require electricity or diesel for operation, so reducing the cost of irrigation, and the zero marginal cost for each additional unit of water incentivizes farmers to increase their cropping intensity.
- SPIPs reduce GHG emissions from agricultural production.
- The reduction in diesel usage also reduces local short-lived climate pollutants such as black carbon.

SPIP is a proven technology for pumping water (Chandel et al., 2015; Sontake and Kalamkar, 2016) and the current challenge for implementers is to increase adoption of the technology. High capital costs are a major impediment for the technology, as at current costs an SPIP is 10–30 times more expensive than a diesel or electric pump (depending on the size of the pump and number of panels) (Dekker, 2015).

In South Asia, the majority of these pumps use groundwater for irrigation. Adoption of this technology has varied in the four countries in our analysis. Bangladesh has established a fee for a service model in which companies or non-governmental organizations (NGOs) can avail themselves of subsidies provided by government, and charge farmers a rate based on their irrigation requirement. India has mainly followed a high-subsidy-led model for uptake of SPIPs. In Nepal, there is no government subsidy for SPIPs, with NGOs piloting demonstration projects to showcase the technology. In Pakistan, in the absence of a national level policy, a high proportion of SPIP users have purchased the system at full cost. In terms of accessibility, the beneficiaries are medium to large farmers in India and Pakistan (Ali et al., 2016; Kishore et al., 2014). However, in Bangladesh, small farmers have benefitted from the innovative financial model (Hossain et al., 2014).

Examination of the literature of solar-powered pumps shows that the majority of published papers are in engineering journals investigating efficiency of the system (Mokeddem et al., 2011), payback period (Jamil et al., 2012), and comparison between various pump types (Parajuli et al., 2014). There have only been a few studies evaluating the impacts of solar pumping interventions on cropping patterns, yields, irrigation methods, and cost savings over time in farmers' fields (IRENA, 2016; Kishore et al., 2017).

## 4.2. Studies

Following the inclusion/exclusion criteria, we could find only three studies in South Asia that have addressed the agricultural impacts of SPIP in experimental or quasi-experimental settings. Two were based in India and one in Pakistan. One of them (Kishore et al., 2017) highlights the paucity of studies analysing the real impacts of providing SPIPs in farmers' fields.

In India, Kishore et al., (2014, 2017) conducted post-implementation surveys of SPIPs. For the first study, the authors analysed within-farmer analysis of gains from utilizing SPIP using a propensity score methodology. They also used treatment-control analysis, where their treatment group was farmers using SPIPs, and the control group was farmers whose plots were adjoined to the command area of the pump. Data were collected for the year 2012–13. The second study followed a simple before–after methodology to measure the impacts of the technology for SPIP owners, and data were collected in December–January in 2012–13. The objective of the study in Pakistan was to identify and analyse factors that influence farmers' adoption of a traditional water pump (electricity) or alternative energy water pumps (diesel, solar, and biodiesel) and the impact on cereal crop yield through a propensity score methodology. Data collection for this study took place in 2014. Information on the three case studies is provided in Table 5.

Table 5: **Studies of SPIP**

| Authors | Year | Country | Location | Methodology |
|---|---|---|---|---|
| Kishore et al. (2017) | 2017 | India | Bihar, India | Actual implementation |
| Kishore et al. (2014) | 2014 | India | Rajasthan, India | Actual implementation |
| Ali et al. (2016) | 2015 | Pakistan | Punjab, Sindh, Khyber Pakhtun Khwa and Balochistan, Pakistan | Actual implementation |

## 4.3. Agricultural Productivity Gains

The first study in Bihar reported higher yields for both paddy (9%) and wheat (11%) for SPIP users. Similarly, farmers' productivity increased by 5%–10% post-SPIP implementation in the Rajasthan study. The Pakistan study reported an increase in yield but did not disentangle the yield increase between diesel, solar, and biodiesel pumps. These can be illustrated in Table 6 below:

Table 6: **Yield change for SPIP**

| Study | Crops | Increase in yield | Percentage change |
|---|---|---|---|
| Kishore et al. (2017) | Paddy, wheat | Yes | 9–11 increase in paddy and wheat cultivation, respectively |
| Kishore et al. (2014) | Orchard cultivation | Yes | 5–10 |
| Ali et al. (2016) | Wheat, rice, maize | Yes | NA |
| N/A, Not applicable | | | |

## 4.4. Water Savings and Productivity

Water use increased in the study in Bihar (Kishore et al., 2017). In the study area, farmers using SPIPs could grow paddy in the entire area, while nearly 40% of land under diesel-powered irrigation was left fallow due to water scarcity and high cost of irrigation.

For the Rajasthan study, farmers reported higher water use for irrigation. Earlier, high marginal costs prevented them from irrigating the fields. However, SPIPs, with their zero marginal costs, led to higher WUE. Water savings were not achieved, owing to higher water usage, and this threatened the over-exploited groundwater resources in western India (as illustrated in detail in Table 7). Innovative schemes (Kishore et al., 2014), such as the Surya Raitha programme launched in the state of Karnataka, are required to provide incentives to farmers and decrease extraction of scarce groundwater resources.

Table 7: **Water savings for solar-powered irrigation pumps**

| Study | Crops | Water saving | Percentage change |
|---|---|---|---|
| Kishore et al. 2017 | Paddy, wheat | No | N/A |
| Kishore et al. 2014 | Orchard cultivation | No | N/A |
| Ali et al. 2015 | Wheat, rice, maize | N/A | |

N/A, Not applicable

## 4.5. Energy Savings

In two of the Indian studies, considerable cost savings in diesel were made, and represented the biggest benefits for users of SPIPs. Kishore et al. (2017) calculate the savings of diesel per hectare (see Table 8). For the Rajasthan study, Kishore et al. (2014) find that the biggest perceived benefit of solar pumps for 79 of the 107 farmers was diesel saving. On average, a solar pump owner expected to save diesel worth INR 48,000–65,000 in one crop year, depending on the pump replaced and cultivation patterns.

Table 8: **Energy savings for solar-powered irrigation pumps**

| Study | Crops | Savings in diesel | INR ha[a] |
|---|---|---|---|
| Kishore et al. 2017 | Paddy | Yes | 3,310 |
| | Wheat | Yes | 2,317 |
| Kishore et al. 2014 | Orchard cultivation | Yes | N/A |

[a]authors' calculations; NA, Not applicable

# 5. Zero Tillage (ZT)

## 5.1. Background

A considerable body of literature has focused on conservation agriculture in South Asia. Within South Asia, a majority of the work focuses on the IGP covering Pakistan, India, Bangladesh, and Nepal. In this region, the predominant staple food crops are rice and wheat, which occupy nearly 13.5 million hectares of agricultural land. (Gupta and Seth, 2007) The area of rice–wheat systems in India, Pakistan, Bangladesh, and Nepal was 10, 2.2, 0.8, and 0.5 million hectares, respectively. (Mahajan et al., 2018). The rice–wheat cropping system is vital in this region, especially for food security, as it allows 400 million people to gain access to the staple grains (Sarwar and Goheer, 2007).

The Green Revolution in India, which took place during the 1960s, helped to increase the productivity of rice–wheat systems. This was possible as a result of the supportive policy environment that encouraged introduction of high-yield varieties coupled with complementary technologies in the form of irrigation and fertilizers (Erenstein and Laxmi, 2008). During the 1990s, various studies observed that the gains from the Green Revolution, especially in the western IGP, was declining. Yields were stagnating and in some instances falling (Gupta and Seth, 2007; Hobbs and Gupta, 2003) because of the continuous cultivation of rice and wheat. Soil organic matter decline lowered irrigation water availability, and the advent of new weeds, pests, and diseases was compounding the issue. Increasing input was required to maintain crop yields, and total factor productivity was declining (Paroda et al., 1994). Planting of the wheat crop for the rabi (winter) season was also being delayed owing to the late harvest of rice. Each day of delay in sowing reduces the wheat yield by 1%–1.5% (Derpsch, et al., 2010). Conservation agriculture emerged as a possible solution to these issues as it involved minimum disturbance of the soil, decreased water consumption, and brought forward the planting date of wheat.

ZT has been the resource-conserving technology most adopted in the IGP (Erenstein, 2009). In this technology, the seed is placed into the soil by a seed drill without prior land preparation (Hobbs and Gupta, 2003). The principal advantages, as mentioned by the farmers in switching to ZT, are:

- cost saving and thus higher profit;
- savings in irrigation water, especially in first irrigation; and
- improvement in soil fertility owing to decomposition of paddy stubbles in the soil.

## 5.2. Studies

Table 9 provides a list of papers in which ZT has been the primary technology of interest. Following the inclusion/exclusion criterion, we checked whether the studies considered the yield, water saving, and energy-saving nature of ZT. We found 29 papers on the subject in South Asia. Most existing studies are based in the Punjab province of Pakistan and Haryana state in India.

Table 9: **Zero tillage studies**

| Authors | Year | Location | Experimental | Methodology |
|---|---|---|---|---|
| Khan et al. | 2009 | Dinajpur, Chuadanga, and Gazipur | Yes | On-farm trial |
| Alam et al. | 2015 | Gazipur, Bangladesh | Yes | On-station trial |
| Gathala et al. | 2016 | Rangpur, Rajshahi, and Comilla, Bangladesh | Yes | On-farm trial |
| Gangwar et al. | 2004 | Uttar Pradesh, India | Yes | On-station trial |
| Gupta and Seth | 2007 | India | No | Review paper |
| Bhattacharya et al. | 2008 | Almora, Uttaranchal, India | Yes | On-station trial |
| Erenstein and Laxmi | 2008 | India | No | Review paper |
| Saharawat et al. | 2009 | Haryana and Uttar Pradesh, India | No | On-station trial |
| Krishna et al. | 2012 | West Bengal, India | No | Actual implementation |
| Tripathi et al. | 2013 | Haryana, India | No | Actual implementation |
| Das et al. | 2014 | New Delhi, India | Yes | On-station trial |
| Krishna and Veettil | 2014 | Haryana, India | No | Actual implementation |
| Keil et al. | 2015 | Bihar, India | No | Actual implementation |
| Aryal et al. | 2016 | Haryana, India | No | Actual implementation |
| Choudhary et al. | 2016 | Punjab, India | Yes | On-station trial |
| Parihar et al. | 2016 | New Delhi, India | Yes | On-station trial |
| Regmi et al. | 2009 | Rupandehi and Kavre, Nepal | No | On-farm trial |
| Tripathi | 2013 | Rupandehi, Nepal | Yes | On-farm trial |
| Hobbs and Gupta | 2003 | Punjab, Pakistan | No | Review paper |
| Sarwar and Goheer | 2007 | Punjab, Pakistan | No | Actual implementation |
| Ahmad et al. | 2007 | Punjab, Pakistan | No | Actual implementation |
| Farooq et al. | 2007 | Punjab, Pakistan | No | Actual implementation |
| Erenstein at al. | 2008 | Haryana, India; Punjab, Pakistan | No | Actual implementation |
| Rehman et al. (part of book chapter in Ladha et al.) | 2009 | Punjab, Pakistan | Yes | On-farm trial |
| Erenstein | 2009 | Haryana and Punjab, India; Punjab, Pakistan | No | Review paper |
| Ladha et al. | 2009 | Indo-Gangetic Plains | No | Review paper |
| Erenstein | 2010 | Haryana, India; and Punjab, Pakistan | No | Actual implementation |
| Ahmad et al. | 2014 | Punjab, Pakistan | No | Actual implementation |

## 5.3. Agricultural Productivity Gains

All the studies we reviewed mentioned yield change from switching to ZT. A summary of the results from the various papers is provided in Table 10.

Table 10: **Yield changes for zero tillage**

| Authors | Country | Crops | Increase in yield | Percentage change |
|---|---|---|---|---|
| Khan et al. (2009) | Dinajpur, Chuadanga, and Gazipur, Bangladesh | Wheat | Yes | 23% increase in yield |
| Alam et al. (2015) | Gazipur, Bangladesh | Rice, potato | Yes | 70% rise in rice equivalent yield |
| Gathala et al. (2016) | Rangpur, Rajshahi, and Comilla, Bangladesh | Maize | Yes | 6% rise in yield as compared to conventional tillage |
| Gangwar et al. (2004) | Uttar Pradesh, India | Wheat | No | 20% fall in yield as compared to conventional tillage |
| Gupta and Seth (2007) | India and Pakistan | Wheat | Yes | 7% rise in yield as compared to conventional tillage |
| Bhattacharya et al. (2008) | Almora, Uttaranchal, India | Rice, wheat | No | 3% and 6% fall in yield over the study period as compared to zero tillage, in rice and wheat respectively |
| Erenstein and Laxmi (2008) | Punjab, Haryana, Uttaranchal, Uttar Pradesh, Bihar, and Madhya Pradesh, India | Wheat | Yes | 6% rise in yield across on-station and on-farm studies |
| Saharawat et al. (2009) | Haryana and Uttar Pradesh, India | Rice, wheat | Ambivalent | 3% fall in rice yield and 1% rise in wheat yield |
| Krishna et al. (2012) | West Bengal, India | Wheat | No | Not significant |
| Tripathi et al. (2013) | Haryana, India | Wheat | Yes | 2% rise in yield as compared to conventional tillage |
| Das et al. (2014) | New Delhi, India | Wheat | Yes | 2% rise in yield as compared to conventional tillage |
| Krishna and Veettil (2014) | Haryana, India | Wheat | Yes | 6% rise in yield as compared to conventional tillage |
| Keil et al. (2015) | Bihar, India | Wheat | Yes | 19% rise in yield as compared to conventional tillage |
| Aryal et al. (2016) | Haryana, India | Wheat | Yes | 12% rise in yield as compared to conventional tillage |
| Choudhary et al. (2016) | Punjab, India | Cotton, wheat | Yes | 6% rise in cotton and 32% rise in wheat yield, respectively |
| Parihar et al. (2016) | New Delhi, India | Maize, wheat, chickpea, mustard, mungbean | Yes | 14% rise in maize equivalent yield as compared to conventional tillage |
| Regmi et al. (2009) | Rupandehi and Kavre, Nepal | Wheat | Yes | 30%–40% higher yield than conventional tillage and broadcast wheat |
| Tripathi (2013) | Rupandehi, Nepal | Wheat | Yes | 16% rise in yield compared to conventional tillage |

| | | | | |
|---|---|---|---|---|
| Hobbs & Gupta (2003) | Punjab, Pakistan | Wheat | Yes | 5% rise in yield as compared to conventional tillage |
| Sarwar & Goheer (2007) | Punjab, Pakistan | Wheat | Yes | 8% rise in yield as compared to conventional tillage |
| Ahmad et al. (2007) | Punjab, Pakistan | Wheat | Yes | 5% rise in yield as compared to conventional tillage |
| Farooq et al. (2007) | Punjab, Pakistan | Wheat | No | 3% fall in yield as compared to conventional tillage |
| Erenstein et al. (2008) | Haryana, India; and Punjab, Pakistan | Wheat | Yes | 3% rise in yield as compared to conventional tillage |
| Rehman et al. (part of book chapter in Ladha et al.) (2009) | Punjab, Pakistan | Wheat | Yes | NA |
| Erenstein (2009) | Haryana and Punjab, India; and Punjab, Pakistan | Wheat | Yes | 5%–7% rise in wheat yield compared to conventional tillage |
| Ladha et al. (2009) | Indo-Gangetic Plains | Rice, wheat | Ambivalent | Fall in rice yield and increase in wheat yield. Percentage change not provided |
| Erenstein (2010) | Haryana, India; and Punjab, Pakistan | Wheat | Yes | 8% rise in yield as compared to conventional tillage |
| Ahmad et al. (2014) | Punjab, Pakistan | Wheat | Yes | Same as Ahmad et al. 2007 |

N/A, Not applicable

We found three contemporary papers mentioning yield differences between ZT and CT for Bangladesh. The first was a 2-year experimental study (Khan et al., 2009) in farmers' fields. The authors observe a decrease in wheat yield in the first year because of uneven germination and weed problems. Zero-till was improved in the following year and yield increased by 23%. In the second paper, Alam et al. (2015) compare various conventional tillage techniques and ZT combined with crop diversification for a rice-based system. Their study methodology was an on-station trial in an experimental site in Bangladesh Agricultural Research Institute. Data were collected for 2009–12. The authors find that there is a rise in yield using ZT and crop diversification in that cereal crop system. The third paper (Gathala et al., 2016) explores the issue of gains from yield for ZT in rice–maize systems. On-farm trials were carried out in three districts in Bangladesh. From data collected over 2009–12 they observe that the system yield for rice–maize using ZT increased by 6% compared to conventional tillage techniques.

There is extensive literature on ZT for India. The majority of the studies have looked at the rice–wheat system and especially the impacts of the technology on wheat cultivation. A review study on ZT studies and their findings was conducted by Erenstein and Laxmi (2008). On-station, on-farm, and farmer survey data show that yield gains were between 5% and 7% on adoption of ZT for wheat. Some studies in India have found an insignificant impact on yield (Bhattacharya at al., 2008; Gangwar et al., 2004). There have been few studies to measure the impact of ZT on rice crops and these found that the yield effect was negative and insignificant in most cases (Ladha et al. ,2009). Some recent studies have highlighted the yield gain from adoption of ZT for wheat in the Eastern Gangetic Plains (Keil et al., 2015), resilience to yield losses owing to climate fluctuations in Haryana, and an increase in crop productivity for cotton (Choudhary et al., 2016; Das et al., 2014) and maize (Parihar at al., 2016).

Two papers analysing ZT in Nepal have found substantial increases in wheat yield. Regmi et al. (2009) observe 30%–40% higher yield in ZT practices compared to conventional tillage practices in the Terai region of Nepal. Tripathi (2013) conducted participatory research experiments in different farmers' fields in Rupandehi district for two successive years (2006–07 and 2007–08). Yields in ZT for wheat were significantly higher (on average 24%)

with respect to conventional tillage techniques. For Pakistan, farm surveys (Erenstein, 2007; Erenstein et al., 2008; Farooq et al., 2007) found that ZT was primarily a cost-saving technology and that there was no significant increase in yield. The lack of increase in yield post-ZT has been a major contributor to slow adoption in Pakistan, and needs to be followed up (Erenstein, 2009).

## 5.4. Water Savings and Productivity

Water savings for ZT predominantly come from the savings in water from the first irrigation. Table 11 provides a synopsis of water savings from various studies.

Table 11: **Water savings for zero tillage**

| Authors | Country | Crops | Water savings | Percentage change |
|---|---|---|---|---|
| Khan et al. (2009) | Dinajpur, Chuadanga Gazipur | Rice | Yes | 40% less water required compared to conventional tillage |
| Alam et al. (2015) | Gazipur, Bangladesh | Rice, potato | Yes | Reduced tillage for rice decreased irrigation inputs by 27% compared to conventional method. Water input for potato (zero tillage) reduced by six times compared to Boro rice. Water productivity increased by 6–12 times |
| Gathala et al. (2016) | Rangpur, Rajshahi, and Comilla, Bangladesh | Maize | No | Increased water use by 10% for zero tillage compared to conventional tillage |
| Gangwar et al. (2004) | Uttar Pradesh, India | | NA | |
| Gupta and Seth (2007) | India and Pakistan | Wheat | Yes | 30%–50% decrease in water for irrigation |
| Bhattacharya et al. (2008) | Almora and Uttaranchal, India | Rice, wheat | Yes | Decrease in water use of 3% for rice and 4% for wheat |
| Erenstein and Laxmi (2008) | India | Wheat | Yes | Across studies savings of 20%–35% for wheat observed |
| Saharawat et al. (2009) | Haryana and Uttar Pradesh | Rice | Yes | Saving in irrigation water between 9% and 13% |
| Krishna et al. (2012) | West Bengal, India | Wheat | NA | |
| Tripathi et al. (2013) | Haryana, India | Wheat | Yes | Saving in irrigation water of 18% |
| Das et al. (2014) | New Delhi, India | Wheat | Yes | Saving in irrigation water of 5% compared to conventional tillage |
| Krishna and Veettil (2014) | Haryana, India | Wheat | NA | |
| Keil et al. (2015) | Bihar, India | Wheat | NA | |
| Aryal et al. (2016) | Haryana, India | Wheat | NA | |
| Choudhary et al. (2016) | Punjab, India | Cotton, wheat | Yes | 22% saving in irrigation water use compared to conventional tillage |

| | | | | |
|---|---|---|---|---|
| Parihar et al. (2016) | New Delhi, India | Maize, wheat, chickpea, mustard, mungbean | Yes | 5% saving in input water compared to conventional tillage |
| Regmi et al. (2009) | Rupandehi and Kavre, Nepal | Wheat | NA | |
| Tripathi (2013) | Rupandehi, Nepal | Wheat | Yes | 40% saving in irrigation cost and time compared to conventional tillage |
| Hobbs and Gupta (2003) | Punjab, Pakistan | Wheat | Yes | 25%–30% saving in water use |
| Sarwar and Goheer (2007) | Punjab, Pakistan | Wheat | Yes | 23% saving in water used for irrigation |
| Ahmad et al. (2007) | Punjab, Pakistan | Wheat | Yes | 5% saving in irrigation water use at field level |
| Farooq et al. (2007) | Punjab, Pakistan | Wheat | Yes | 7% saving in water use |
| Erenstein et al. (2008) | Haryana, India; and Punjab province, Pakistan | Wheat | Yes | Haryana study shows a statistically significant water saving of 13.4% compared to conventional tillage |
| Rehman et al. (part of book chapter in Ladha et al.) (2009) | Punjab, Pakistan | Wheat | Yes | Percentage change not provided |
| Erenstein (2009) | Haryana and Punjab, India; and Punjab, Pakistan | Wheat | Yes | Percentage change not provided |
| Ladha et al. (2009) | Indo-Gangetic Plains | Rice, wheat | Yes | Increase in water savings for both rice and wheat; percentage change not provided |
| Erenstein (2010) | Haryana, India; and Punjab, Pakistan | Wheat | NA | |
| Ahmad et al. (2014) | Punjab, Pakistan | Wheat | Yes | Same as Ahmad et al. 2007 |

N/A, Not applicable

At country level, Alam et al. (2015) found that in Bangladesh water saving and water productivity for ZT were substantially greater than conventional technology. Gathala et al. (2016) found more irrigation requirements in ZT for maize compared to conventional technology. Permanent beds were superior in decreasing irrigation usage, following authors' calculations.

According to an Rice-Wheat Consortium of the Indo-Gangetic Plains (RWC) report (2005) for wheat, farmers believe that in ZT there are water savings of 30%–50% in the first irrigation and 15%–20% in subsequent irrigations for wheat. (Seth et al., 2003). Researchers find that 36% less water was used (Ladha et al., 2009) post-ZT.

Wheat water productivity (kilogram of grain produced per unit water depleted) was found to be higher with ZT because of the more efficient use of residual moisture left over from the rice crop. Water productivity for rice–wheat systems was found to be higher in India than in similar regions in Pakistan because of differences in crop management practices (Ladha et al., 2009). Erenstein and Laxmi (2008) found that ZT was associated with irrigation water savings of 20%–35% for wheat crops compared to CT (conventional tillage), with reductions in water use of about 10 cm ha–1, or approximately 1 million l ha–1. In tube well irrigation they found water savings of 13% with ZT. Predominantly, the savings in irrigation water are because of reduced duration of first irrigation. A few studies of ZT have also reported savings in one irrigation because of earlier planting of wheat. The authors conclude from the review of studies that ZT wheat enhances WUE, reduces irrigation requirements, and thereby helps save irrigation water. Recent papers on cotton–wheat systems (Choudhary et al., 2016; Das et al., 2014) investigating impacts of ZT found a similar rise in water productivity and efficiency. In a Nepal Terai study conducted by Tripathi (2013), irrigation costs fell by 40% after adoption of ZT.

Studies in Pakistan have highlighted WUE in the rice–wheat system (Farooq and Erenstein, 2007; Iqbal et al., 2002; Kahlown et al., 2006). Ahmad et al. (2007) delve deeper into the issue of water savings for rice–wheat systems at a basin level with respect to utilizing resource-conserving technologies like ZT. As observed in previous studies in Pakistan (Hobbs and Gupta, 2003; Sarwar et al., 2007), ZT does decrease water use at field level. But, owing to increasing profitability as a result of water savings, the cropping area might be expanded, leading to further depletion of aquifers in the western IGP. Ahmad et al. (2007) look further into this issue. They combine biophysical approaches at a range of scales with socioeconomic data and theory, and observe that water savings at farm level could result in additional water depletion at farm and higher system level, due to increased cropping intensity or expanded crop area.

## 5.5. Energy Savings

Energy savings in ZT occur predominantly through savings in land preparation and cost establishment (i.e., a decrease in tillage and savings in irrigation). Most papers report total cost savings or net benefit from switching to ZT. A synopsis of energy savings for the various studies is provided in Table 12.

Table 12: **Energy savings for zero tillage**

| Authors | Country | Crops | Energy Savings | Percentage change |
|---|---|---|---|---|
| Khan et al. (2009) | Dinajpur, Chuadanga, and Gazipur, Bangladesh | Rice | Yes | |
| Alam et al. (2015) | Gazipur, Bangladesh | Rice | Yes | Energy requirement for reduced tillage of rice is lower. Energy inputs for potato – such as seed, labour, and fertilizer – is higher than for Boro rice |
| Gathala et al. (2016) | Rangpur, Rajshahi, and Comilla, Bangladesh | Maize | Yes | About 2.5% reduction in energy use for zero tillage compared to conventional tillage |
| Gangwar et al. (2004) | Uttar Pradesh, India | Wheat | NA | |
| Gupta and Seth (2007) | India and Pakistan | Wheat | Yes | Numbers not provided |
| Bhattacharya et al. (2008) | Almora, Uttaranchal, India | Rice, wheat | NA | |
| Erenstein and Laxmi (2008) | India | Wheat | Yes | 81% savings in energy costs |
| Saharawat et al. (2009) | Haryana and Uttar Pradesh, India | Rice, wheat | NA | |
| Krishna et al. (2012) | West Bengal, India | Wheat | NA | |

| | | | | |
|---|---|---|---|---|
| Tripathi et al. (2013) | Haryana, India | Wheat | Yes | 46% savings in machine labour costs |
| Das et al. (2014) | New Delhi, India | Wheat | NA | |
| Krishna and Veettil (2014) | Haryana, India | Wheat | Yes | 63%–77% savings in machinery costs |
| Keil et al. (2015) | Bihar, India | Wheat | NA | |
| Aryal et al. (2016) | Haryana, India | Wheat | NA | |
| Choudhary et al. (2016) | Punjab, India | Cotton, wheat | Yes | 16% savings in energy inputs |
| Parihar et al. (2016) | New Delhi, India | Maize, wheat, chickpea, mustard, mungbean | NA | |
| Regmi et al. (2009) | Rupandehi and Kavre, Nepal | Wheat | NA | |
| Tripathi (2013) | Rupandehi, Nepal | Wheat | Yes | 63% savings in land preparation cost compared to conventional tillage |
| Hobbs and Gupta (2003) | Punjab, Pakistan | Wheat | NA | |
| Sarwar and Goheer (2007) | Punjab, Pakistan | Wheat | Yes | 40% savings in irrigation water costs |
| Ahmad et al. (2007) | Punjab, Pakistan | Wheat | NA | |
| Farooq et al. (2007) | Punjab, Pakistan | Wheat | Yes | 84% savings in diesel use for tillage operations |
| Erenstein et al. (2008) | Haryana, India; and Punjab province, Pakistan | Wheat | Yes | 80% savings in diesel consumption for tillage operations |
| Rehman et al. (part of book chapter in Ladha et al.) (2009) | Punjab, Pakistan | Wheat | Yes | N/A |
| Erenstein (2009) | Haryana and Punjab, India; and Punjab, Pakistan | Wheat | Yes | N/A |
| Ladha et al. (2009) | Indo-Gangetic Plains | Rice, wheat | NA | |
| Erenstein (2010) | Haryana, India; and Punjab, Pakistan | Wheat | NA | |
| Ahmad et al. (2014) | Punjab, Pakistan | Wheat | NA | |

N/A, Not applicable

For the Bangladesh study, Alam et al. (2015) found that energy input use for ZT is lower than that for CT (conservation tillage).

In the review of ZT studies for India, Erenstein and Laxmi (2008) calculate an average total cost saving of INR 2,320 ha−1 (USD 1 = INR 48) for adopters of the technology. About three-quarters of the savings were from reduction in tillage. Jat et al. (2014) found that ZT in both rice and wheat provides an additional net return by USD 459 ha−1 compared with a system based entirely on CT. Net returns were higher in the cotton–wheat system trials (Choudhary et al., 2016; Das et al., 2014).

In Nepal, Tripathi (2013) and Regmi et al. (2009) report a benefit of 63% for farmers switching to ZT. Studies in Pakistan have also reported the cost-saving nature of ZT (Ladha et al., 2009; Sarwar and Goheer, 2007). Farooq et al. (2007) compare between adopters and non-adopters of ZT and observe a significant rise in net revenue for adopters. This net revenue gain is insignificant for adopters of ZT if we compare between plots adopting ZT and those using conventional tillage. The overall gain from adoption of ZT is, therefore, ambiguous.

# 6. Coping with Climate Extremes

The climate smart agriculture technologies prove to be vital in terms of coping with climate extremes. In an age of increasing climate variability, these agricultural water management techniques provide respite for farmers through efficient water management in agriculture.

MI technologies typically reduce the risk of water supply shortages during drought or in semi-arid or arid areas because of their high efficiency (less non-beneficial soil–water evaporation, wind draft, evaporation of canopy-intercepted water) (Zotarelli et al., 2015).

Kishore et al. (2014) find that the availability of SPIPs has enabled farmers to become more resilient to weather fluctuations that have become relatively common due to climate change, increasing incidences of drought and delayed monsoons being the prime examples. As mentioned earlier, farmers using SPIPs can cultivate a larger area during a drought owing to increased water availability.

In the same vein, conservation agriculture – of which ZT is a part – combats untimely rainfall with better water infiltration. Aryal et al. (2016) represents the only paper written in a South Asian context that explores the adaptive and risk-bearing capacity of conservation agriculture under climatic extremes. All the farmers who adopted conservation agriculture believe that a better root system is the main reason why it adapts better to changes in rainfall patterns. About 35% of adopters consider that better water infiltration in conservation agriculture-based wheat production system (CAW) as compared to conventional tillage-based wheat production system (CTW) reduces yield losses.

The paper provides evidence that conservation agriculture-based practices in wheat are an effective adoption response to the excessive and untimely rainfall events becoming more frequent in northern India. Another paper (Parihar et al., 2016) also mentions that conservation agriculture practices provide resilience in erratic climatic conditions.

# 7. Paradox of Irrigation System Modernization

Studies exploring the links between irrigation water use and energy consumption have shown that energy consumption can be reduced when pressurized systems are used in groundwater regions (Hodges et al., 1994; Srivastava et al., 2003). Jackson et al. (2010) find that converting from flood to pressurized systems results in a reduction in water application of between 10% and 66%. Similarly, in the groundwater-dependent region, energy consumption reduced by 12%–44%. In contrast, in the surface water-supplied region, it resulted in energy consumption being increased by up to 163%. Hence, it can be observed that the benefits of both water saving and energy saving can be obtained simultaneously through pressurized irrigation systems in groundwater-dependent regions. In a surface water-supplied region, Jackson et al. (2010) propose a gravity-fed irrigation system to improve WUE.

In theory, more efficient irrigation systems and better irrigation scheduling lead to significant simultaneous energy and water savings (Rodríguez-Diaz et al., 2011). However, as a result of water saving achieved through efficient irrigation, there would be a tendency for the farmers to pump more water as they look to expand their irrigated area. This, in turn, would mean an increase in energy consumption through more use of the pumps. Optimizing one aspect of a system can have unintended resource and environmental consequences: an increase in energy consumption patterns of irrigated crops (Jackson et al., 2010).

Additionally, improving the efficiency of water use is usually presented as an opportunity for large water savings in the agricultural sector. However, this may not translate into reduced consumption and this phenomenon is associated with the rebound effect or Jevons paradox (Dumont et al., 2013). The principal explanation is linked to the reduction in relative cost of water per unit of output (UNEP, 2012) potentially accompanied by a reduction in the absolute price of water (EEA, 2012). In line with that, an increase in demand would occur if water was initially limited by its price. This can also be pointed out by Llop (2008), who identify that any type of improvement in technical efficiency of water requirements reduces water demand causing price of water to decrease. The price reduction leads to increase in water use which ends up cancelling out the initial efficiency completely or partially.

The only flaw in this school of thought is that price rarely constrains water use, particularly in the agricultural industry (Hellegers and Perry, 2006). As water use is generally inelastic to price change, it is problematic to associate a reduction in the price of water to subsequent increase in demand. Therefore, the rebound effect can be better explained by identifying unintended consequences. A study done by Lecina et al. (2010) points to efficiency improvements leading to higher water consumption, primarily owing to the efficacy of the technology used (i.e., sprinkler systems). Their observations associate the consumption increase to higher land productivity and a shift to more profitable and water-intensive crops.

Hence, it is vital to note that conserving water as a result of efficient water management through use of pressurized technology (drip irrigation, sprinklers, and SPIPs) may lead to increased water consumption. In turn, this could lead to an increase in pump use, resulting in a rise in energy costs. It appears that conserving water or achieving water savings relate to increases in energy costs. The important thing to note here is that water saving in itself triggers more use of water, and that results in more pumping of water, leading to a rise in energy costs.

# 8. Conclusion and way forward

On average, adoption of MI, ZT, and SPIPs tends to benefit the adopters on all three fronts: yield enhancement, water savings, and energy savings. While all these benefits may increase in field-level studies, water and energy consumption will rise if we consider basin-level adoption. Findings suggest that, in regions where land has been left fallow or unirrigated owing to water shortages, adoption of AWM technologies leads to expansion of the command area (Ahmad et al., 2014; Kishore et al., 2014; Kumar et al., 2008). This translates into an increase in yield because of a rise in the cultivated area, but could lead to further depletion in regions suffering from groundwater scarcity. Hence, it is imperative to acknowledge that the water-saving capabilities of AWM technologies may, in turn, end up increasing water consumption, thereby also leading to a rise in energy consumption.

Our review shows that no studies have conducted farm-level surveys following a randomized control trial (RCT) methodology. The treatment and control groups selected for the surveys in the studies reviewed were not randomized, and as a result there may be a bias in the results reported. An RCT minimizes bias because the treatment and control groups are randomized, and so its methodology should be pursued in future research into adoption of these technologies. Moreover, the study area of a majority of the papers reviewed are in the plains of South Asia. Only a few AWM studies (Bhattacharya et al., 2008; Kumar et al., 2009; Randev, 2015) have evaluated the impact of our shortlisted technologies in hilly regions. More studies are required to measure the benefits of CSA in such terrain.

# Appendix 1 - Climate Smart Technologies

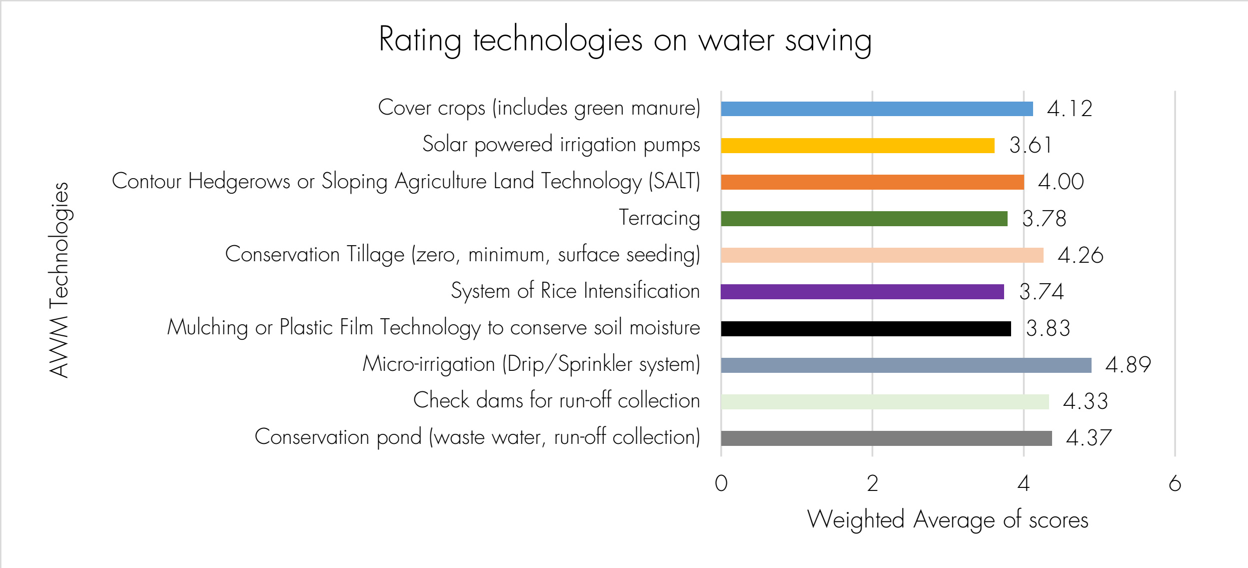
| Water smart technologies | |
|---|---|
| Rainwater management<br><br>Collection and management of rainwater runoff to increase water availability for domestic and agricultural use and ecosystem sustenance | Laser land levelling<br><br>Levelling the field to desired slope using a guided laser beam. Ensures land is level (traditional levelled or unlevelled lands lead to water logging conditions in low-lying areas and soil water deficit at higher spots) |
| Green manure<br><br>Ploughing under or soil incorporation of any green manure crops when green or soon after flowering (e.g., mustard, cowpea, soybean) | Crop rotation<br><br>Successive planting of different crops on the same land to improve soil fertility and productivity and to conserve water |
| Intercropping<br><br>A multiple cropping practice involving growing two or more crops in proximity | Agroforestry (alley cropping, field windbreaks, riparian forest buffers)<br><br>Alley cropping: It is the cultivation of crops between rows of trees<br><br>Riparian forest buffer: natural or re-established streamside forests made up of trees, shrubs, and grasses<br><br>Field windbreaks: protect a variety of wind-sensitive crops, control wind erosion, and increase bee pollination and pesticide effectiveness |
| Cover crops<br><br>Used to maintain soil health and water retention (e.g., wheat, mustard) | System of rice intensification<br><br>Increases productivity of rice by changing the management of plants, soil, water, and nutrients. Also used in other crops (e.g., wheat, millet, sugarcane, pulses) |
| Furrow-irrigated raised bed<br><br>Growing crops on ridges or beds; irrigation applied through furrows separating the beds | Drip-irrigation systems<br><br>Water is applied close to the plants so that only the part of the soil in which the roots grow is wetted |
| Clay pot<br><br>Subsurface irrigation using unglazed indigenous earthen pot with micropores in its wall | Crop diversification (maize–wheat cropping)<br><br>Addition of new crops or cropping systems to agricultural production, taking into account the different returns from value-added crops. |

| | |
|---|---|
| Drought-tolerant varieties<br>Drought-tolerant seeds | Aerobic rice<br>Crop can be dry direct-seeded or transplanted, and soil is kept aerobic throughout the growing season. Varieties mostly planted where irrigation water is scarce and rainfall is low.<br>The concept is to try and combine the drought-resistant characteristics of upland varieties with the high-yielding characteristics of lowland varieties |
| Conservation agriculture<br>FAO definition: "Involving a process to maximize ground cover by retention of crop residues and to reduce tillage to the absolute minimum while exploiting the use of proper crop rotations and rational application of inputs fertilizers and pesticides to achieve a sustainable and profitable production strategy for a defined production system." (FAO 2008) | |
| Energy smart technologies | |
| Direct-seeded rice<br>Cost-effective establishment method where dry seed is drilled into non-puddled soil. Includes proper land levelling and effective weed control measures | Zero tillage/minimum tillage<br>A soil conservation system with the goal of minimum soil manipulation; does not turn the soil over |
| Renewable energy for irrigation<br>Use of renewable energy source (e.g., solar, biogas, wind for operating irrigation pumps) | |

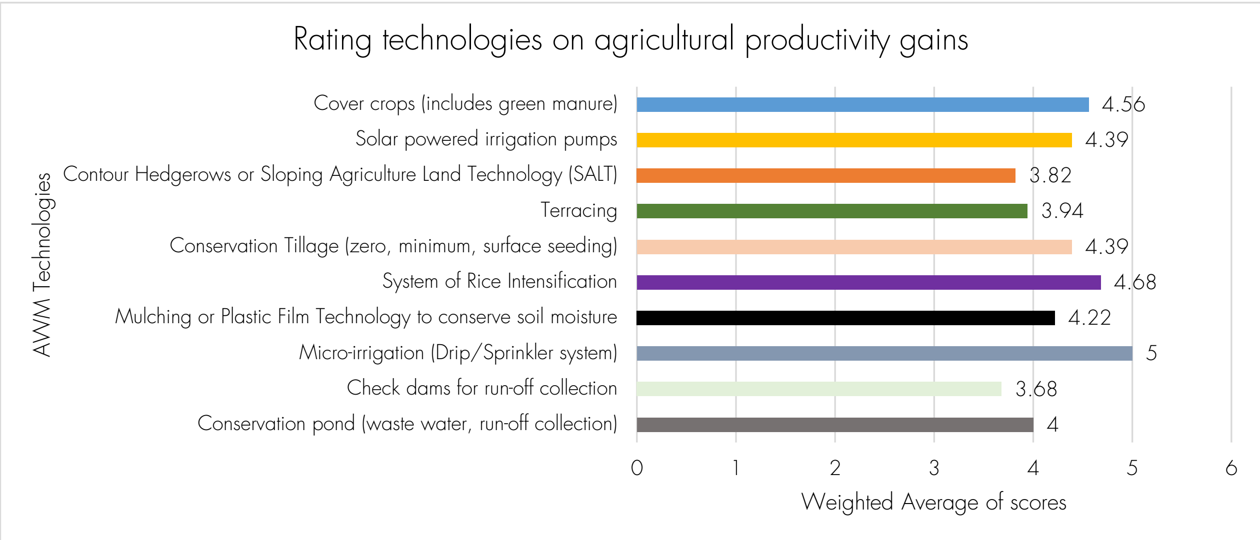
FAO, Food and Agriculture Organization of the United Nations

# Appendix 2 - SurveyMonkey Results

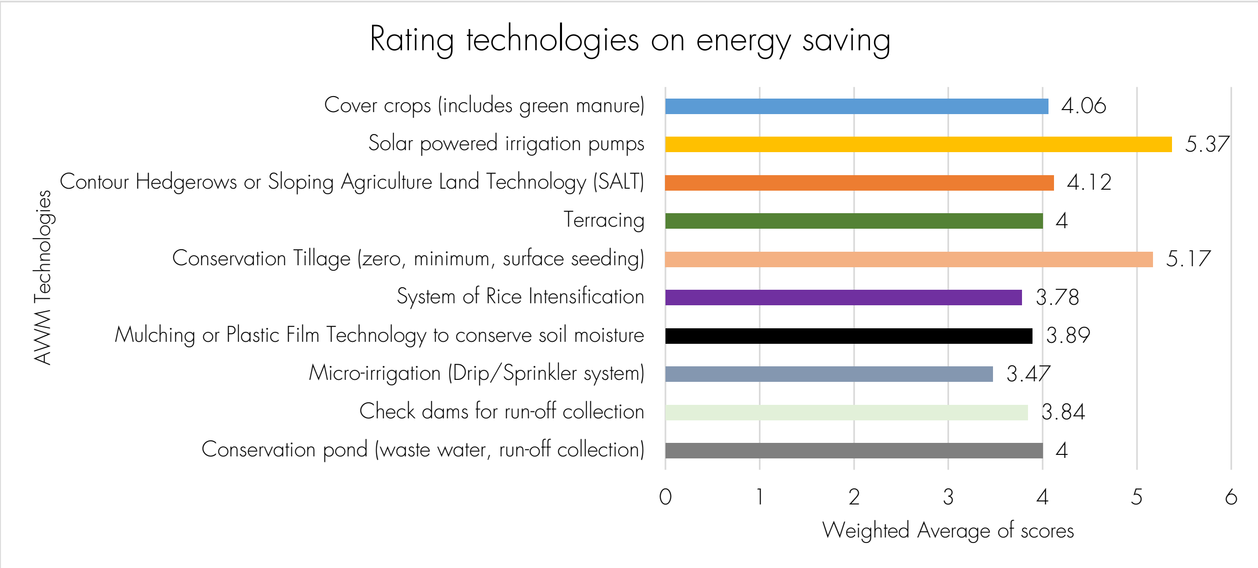
## Water saving (agriculture water management)



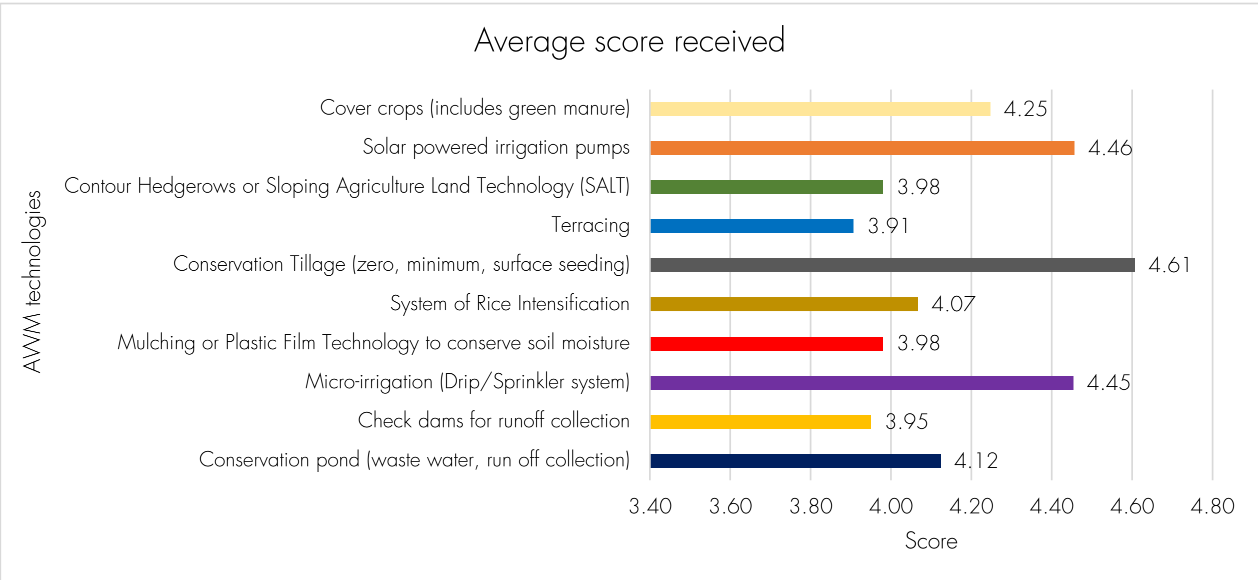

## Agricultural productivity gains (agriculture water management)



## Energy saving (agriculture water management)




## Ranking of technologies (agriculture water management)



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