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Editor's Choice

REVIEW

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# Alternate wetting and drying in Bangladesh: Water-saving farming practice and the socioeconomic barriers to its adoption

**Karen A. Pearson**[1] | **Gearoid M. Millar**[2] | **Gareth J. Norton**[3] | **Adam H. Price**[3]

[1]Science and Advice for Scottish Agriculture, Edinburgh, UK

[2]School of Social Science, University of Aberdeen, Aberdeen, UK

[3]School of Biological Sciences, University of Aberdeen, Aberdeen, UK

**Correspondence**
Adam H. Price, School of Biological Sciences, University of Aberdeen, Aberdeen, UK.
Email: a.price@abdn.ac.uk

**Funding information**
University of Aberdeen

**Abstract**

Water saving in irrigated agriculture is a critical issue for global food security, and much research has suggested substantial benefits of management systems designed to achieve it. Yet there are likely to be socioeconomic barriers which must be understood if these systems are to be adopted. Here, we highlight one example, Alternate Wetting and Drying (AWD) in Bangladesh. In Bangladesh, almost half of the workforce is engaged in agriculture and many people are dependent on rice as their staple food, sometimes consuming it three times per day. Rice production, therefore, is central both to economic well-being and to food security in Bangladesh. However, this sector also faces a number of troubling problems. These include an electricity supply over-stressed by irrigation pumps during the dry season, the gradual depletion of groundwater as a result of unsustainable use, the consumption of rice grains with elevated arsenic content, and the significant emission of rice-based methane into the atmosphere. Interestingly, for more than a decade, evidence has indicated that AWD—an innovative farming practice—holds the promise of mitigating each of these threats to some degree and has been promoted by the Bangladeshi government. However, evidence seems to indicate that it has not been widely adopted in Bangladesh. This paper reviews the existing literature on AWD, related policies in Bangladesh, and the barriers to its uptake among farmers. The complicated relationship between agricultural and socioeconomic systems represents a key barrier to the successful use of AWD among Bangladeshi farmers. Similar barriers to water-saving strategies are likely to exist in other countries and regions, and overcoming these barriers will be essential for AWD to be adopted. The case of Bangladesh provides important indications of how this might be achieved.

**KEYWORDS**

agricultural systems, alternate wetting and drying, irrigation, rice, socioeconomic systems

## 1 | INTRODUCTION

As one of the world's top three most important crops, rice (*Oryza sativa* L.) is the plant that provides the most food for people and is especially important for the planet's poor (GRiSP, 2013). The relationship between rice production, human health, and environmental sustainability in Bangladesh could be considered relevant to many low- and middle-income countries in Asia whose diet is dominated by rice. Agriculture is the foundation of the Bangladesh economy, contributing 17.2% to GDP and employing 45.6% of the workforce (BSS statistical yearbook of Bangladesh 2014, in Kabir, Alauddin, & Crimp, 2017). Rice is the main staple crop, covering about 79% of net cultivated area, and as it can be grown in three seasons, it has an average cropping intensity of 190% (BSS yearbook of agricultural statistics 2014, in Kabir et al., 2017). With a population density of about 1,016 people per $km^2$, Bangladesh is also the most densely populated country on earth (excluding a few small states such as Bahrain and Malta) (Mainuddin & Kirby, 2015), making crop area a limited resource. This has driven the development of a uniquely intensive agricultural production system, taking place over multiple cropping seasons on very small family farms (Headey & Hoddinott, 2016; Majumder, Bala, Arshad, Haque, & Hossain, 2016).

Since the 1970s and 1980s, green revolution technologies of improved irrigation infrastructure, access to chemical fertilizers and pesticides, increased mechanization, and improved varieties have greatly increased rice yields in Bangladesh (Molitor, Braun, & Pritchard, 2017). Today, 62% of farmers use only groundwater for irrigation while 11.3% use surface water. Only 9.2% do not irrigate and rely on rainwater (Ahmed et al., 2013). While diesel is used to power irrigation pumps in 66.6% of cases, 31.9% of farmers are reliant on electricity from the national grid (Ahmed et al., 2013). This puts a significant stress on the national power grid during the dry season. However, at a nation-wide level a total rice yield of just 13.6 million tonnes in 1981/1982 has increased to 32.0 in 2009/2010 (Mottaleb, Mohanty, & Nelson, 2014), and 34.7 in 2015/2016 (Bangladesh Bureau of Statistics) and, as rice cultivation area has not increased (some authors argue that it has decreased due to encroachment by urban areas and sea level rises), this demonstrates the benefits that improved technology—and particularly irrigation during the dry season—has brought. In 2015/2016, 54.5% of total rice yield was produced in the dry (Boro) season (Bangladesh Bureau of Statistics; Figure 1a).

However, rice production in Bangladesh also faces multiple challenges. Islam and Nursey-Bray (2017) have argued that establishing groundwater irrigation in some areas has been maladaptive in the context of our changing climate, as it has been undertaken without thought to its long-term impacts, such as aquifer depletion and increasing salinity which climate change and rising sea levels make increasingly likely. A second problem is the stress on the supply of electricity caused by pumping water for irrigation in the dry season, which spurs problematic load shedding due to the lack of supply which interrupts provision to urban areas. A third problem relates to the high levels of arsenic present in Bangladeshi groundwater (Kundu, van Vliet, & Gupta, 2016; Loewenberg, 2016). In addition to drinking water, arsenic is introduced into people's diets through rice consumption (Meharg & Rahman, 2003). Indeed, for families in areas with low to medium arsenic contamination of drinking water, food may be the main source of exposure to arsenic (Mondal et al., 2010). Another problem associated with rice production is methane emissions. The anaerobic environment of the paddy field promotes the conversion

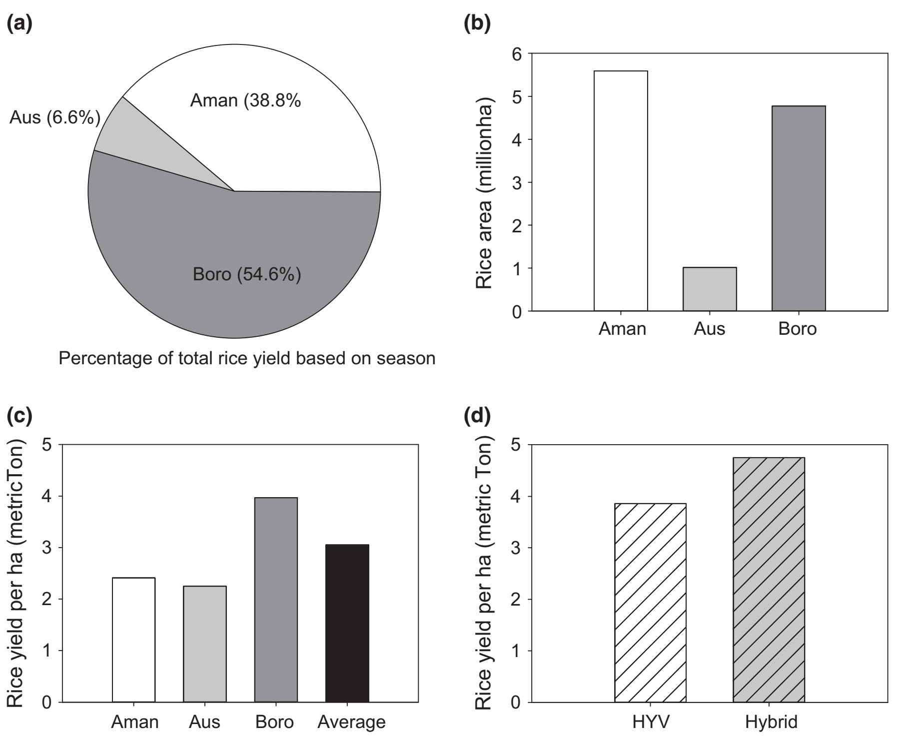


**FIGURE 1** Rice yield data based on season 2015/2016 data. (a) Percentage contribution of the three rice-growing season to total rice production in Bangladesh. (b) Total area crop in the three rice-growing seasons in Bangladesh. (c) Rice yields in growing seasons and the average yield across all three seasons. (d) Yield of high-yielding varieties (HYV) and hybrid cultivars in the Boro season. Data taken from the Bangladesh Bureau of Statistics

of soil organic matter to methane to such an extent that rice fields contribute 15%–20% of anthropogenic methane emissions (Aulakh, Wassmann, & Rennenberg, 2001; Yan, Yagi, Akiyama, & Akimoto, 2005). Given the strong global warming potential of methane, it has been estimated that its emission from rice fields accounts for 11% for all the agriculture-attributable global warming caused by anthropogenic greenhouse gases and 1% of all anthropogenic sources (Smith, 2012).

However, there is an existing model of farmer practice which has been shown to decrease water use and rice grain arsenic significantly, while also having no impact on rice yield and lowering the amount of methane released from rice production (Linquist et al., 2015). This is Alternate Wetting and Drying (AWD), whereby the soil is not kept continuously flooded. Instead, it is allowed to drain for a period of one or more days after the ponded water has disappeared, before being re-flooded (Lampayan, Rejesus, Singleton, & Bouman, 2015). Work into AWD as a water-saving technique first began in China and India in the 1980s and 1990s (Mushtaq, Dawe, Lin, & Moya, 2006). AWD was first evaluated as a water-saving practice in the Philippines in 2002, and first trialed in Bangladesh in 2005 at the Bangladesh Rice Research Institute (BRRI) (Lampayan, Rejesus, et al., 2015). However, all evidence indicates that while AWD has been trialed and demonstrated to farmers repeatedly over the past decade, there is little uptake of the practice by farmers in their own fields independent of demonstration and extension activities, and subsidies. While there have been few substantive social science studies examining the case, existing evidence points to the complicated relationship between agricultural and socioeconomic systems as a key barrier to the successful use of AWD among Bangladeshi farmers.

In this paper, we use Bangladesh as a case study for the adoption of AWD, specifically on what are the barriers to AWD uptake and to shed light on the probable limitations to such adoption in a variety of other cases. The paper continues in four sections. The first reviews the literature on the agricultural system in Bangladesh, including details regarding the inputs necessary for and social dynamics of this system. The second reviews the literature on AWD itself, the impacts it has been evidenced to have, and AWD's reported results in Bangladesh. The third, in turn, describes the challenges to AWD in Bangladesh specifically and focuses on the socioeconomic systems related to land ownership and control of water sources for irrigation. The major finding for this study indicates that it is the relationship between the agricultural system and the socioeconomic system that raises the greatest barriers to widespread adoption of AWD. Finally, the conclusion describes paths for necessary future research and specifically calls for interdisciplinary examination of AWD as a farming practice within complex socioeconomic systems.

## 2 | RICE AGRICULTURE SYSTEMS IN BANGLADESH

A key aspect in the adoption of any new agricultural technology is the understanding of the current status of the agricultural system. In this section, the agricultural system in Bangladesh is reported.

Bangladesh has a monsoon climate with a 4-month wet season and an 8-month dry season (De Heer & Jenkins, 2012). The three possible rice cultivation seasons in Bangladesh are known as *aman* or wet season, *aus* or spring season (which is partially irrigated), and *boro* or dry season (which is fully irrigated). *Aman* and *boro* are the main rice-growing seasons (Figure 1b). Intensive rice cultivation takes place particularly in the northern part of Bangladesh which has a humid subtropical climate (Ahmad, Kirby, Islam, Hossain, & Islam, 2014). *Boro*, or irrigated dry season rice, is the main crop in this area, and it is the highest yielding of the three rice seasons (Ahmed et al., 2013; Figure 1c). The Bangladesh Bureau of Statistics (2015/2016) gives the average yield figures for *boro* rice as 3.86 tonnes/ha when sown with high-yielding conventional varieties, and an average of 4.75 tonnes/ha when sown with hybrid varieties (Figure 1d). Both figures are substantially higher than the national average for rice yields over all seasons, which is 3.05 tonnes/ha.

As the Boro season is the highest yielding of the three seasons and the season most dependent on irrigation, it should be clear that irrigated water is one of the key inputs necessary for rice production in Bangladesh. Although the drilling of tubewells increased greatly after independence, it was the policy reforms that the Bangladesh government introduced in 1988 to remove diesel duty and standardization criteria for machinery which allowed the proliferation of farm machinery, including pumping and well machinery in the 1990s (Hossain, 2009). Although many households cannot afford to own agricultural machinery (only 2% of farmers own a pump which is the most widely owned piece of machinery), most owners of machinery tend to also operate as service providers for other farmers, providing irrigation water or tilling land, for example (Mottaleb, Krupnik, & Erenstein, 2016). These custom hiring agreements mean that most households can access machinery services (Mottaleb et al., 2016). It is likely that similar arrangements exist for accessing other machinery such as two-wheeled tractors for tilling and power threshers.

Water and farming machinery are not the only necessary inputs. The Bangladeshi government also provides fertilizer subsidies to increase farm productivity and technical efficiencies, encouraging farmers to produce more rice (Majumder et al., 2016). In 2010, nearly 50 billion taka (0.7% of GDP) was spent on urea subsidies, with the level of subsidy varying with the season (Bell, Bryan, Ringler, & Ahmed, 2015). Indeed, farmers may under-apply fertilizers other than urea as they are not subject to the same subsidies. Nationally, and across all crops and seasons, 60.3% of households use fertilizer (Zezza et al., 2011). Pesticide usage in Bangladesh is lower than in other southern Asian countries. This is partially due to limited funds restricting farmer access; however, pesticide usage is likely to increase as wealth or access to credit increases (Robinson, Das, & Chancellor, 2007). Across all crops and seasons, 40.5% of households use pesticides (Zezza et al., 2011).

Finally, new rice varieties have been key to Bangladesh's modern rice agriculture system. Bangladesh has been very successful in adopting high-yielding varieties and other green revolution technologies to boost yields significantly since independence, with rice yields increasing 150% since the 1960s (Headey & Hoddinott, 2016). Modern rice varieties have contributed greatly to the increased rice yields seen in Bangladesh and between 1987/1988 and 2000 the proportion of cultivated area under modern rice varieties increased from 37% to 85% (Sen, 2003). At the country level, recent rice yields have been reported as 31.97 million tonnes in 2009/2010 (Mottaleb et al., 2014), and 34.36 million tonnes in 2013/2014 (Azad & Rahman, 2017).

It is reported that the newest hybrid rice *boro* season varieties from the Bangladesh Rice Research Institute (BRRI) have a potential yield of 8–9 tonnes/ha (Mainuddin & Kirby, 2015). It is not likely that this potential will be widely met given that this is the average yield achieved for rice produced in Arkansas (Adhya, Linquist, Searchinger, Wassmann, & Yan, 2015), hybrid varieties are not very popular in Bangladesh, and they attract a lower market price (Spielman, Ward, Kolady, & Ar-Rashid, 2017). The average yield for hybrid *boro* season rice in 2011 was only 4.6 tonnes/ha (Ahmed et al., 2013) and 4.75 tonnes/ha in 2015/2016 (Bangladesh Bureau of Statistics).

In addition to these dynamics related to the seasons, the availability of inputs, and yield, the rice agriculture system in Bangladesh is also closely related to prevalent socioeconomic dynamics. Average farm holdings, for example, are decreasing in size and becoming increasingly fragmented as a result of intergenerational land division, and also through encroachment of urban land and sea level rise (Feldman & Geisler, 2012; Molitor et al., 2017). Several authors estimate the average landholding size in Bangladesh, from the high of 0.68 ha to the low of 0.4 ha (Chowdhury, 2016; Zezza et al., 2011; respectively). Fragmentation of holdings is also a difficulty faced by farmers in Bangladesh. From the BIHS, Ahmed et al. (2013) report that Bangladesh-wide the mean number of patches owned by a household was 3.67, and that this differed by Division, with the Division level averages ranging from 2.76 to 4.92. These figures are lower than Rahman and Rahman (2008), who state that from the Bangladesh Bureau of Statistics Census of Agriculture 1996, the average number of fragments held is 6.

Holding size is also related to landownership status, with 37% of farmers cultivating only their own land, 34% being pure tenants, and 29% cultivating their own land plus rented or sharecropped land (Ahmed et al., 2013). Using data from the BIHS, Kieran, Sproule, Doss, Quisumbing, and Kim (2015) state that 35% of the population are landowners, and 29% hold documented land. This contrasts with Ahmed et al. (2013) who use the same survey results to state that 43% of the population own land. This difference may be explained by the authors using different bottom thresholds for minimum size. The data suggest that many of the holdings of the poorest are too small to support a household at all, with the bottom 25% owning just 3.7% of cultivatable land while the top 10% own 39.8% (Ahmed et al., 2013). In short, the size of a household's landholding is related to their likelihood to experience poverty. Households which were defined as in poverty in 1987/1988 and remained so in 2000 had an average of 0.24 ha, whereas households which were not in poverty in 1987/1988 or 2000 had an average of 1.29 ha (Sen, 2003). Owner occupiers also tend to be more efficient than tenants or sharecroppers as they can keep the best land and rent out relatively poorer quality land (Rahman & Rahman, 2008).

It is also useful to note that different types of rental agreement are in-place for tenant farmers. In the Barind region, the Munda ethnic minority tend to farm land which they rent from Muslim Bengalis (Sharmeen, 2014). Traditionally, they have a *Adhi* or wet season sharecropping contract where they keep a 50% share of the harvest after providing soil preparation, sowing, weeding, and the cost of hired labor in exchange for the landowner providing the land and other inputs (mainly seeds and fertilizer). In the dry season, they have a *Phuran* contract, which means they bear full responsibility for the crop in exchange for a fixed share of the harvest. The introduction of deep tubewells in the area in 1999 hugely increased the profitability of dry season crops, and landowners sought to control access to the new water sources to secure a higher reward from *boro* production (Sharmeen, 2014). This example is one of many complicated rental agreements which are likely to exist throughout Bangladesh.

Complicating this further, Kieran et al. (2015) also report information on land ownership by gender in Bangladesh. Although Bangladeshi law stipulates than women inherit half the share of their brothers, in practice, the proportion of women owning land in Bangladesh is very small. Culturally, the practices of *benami* (where land is held in a woman's name but controlled by her husband) or *naior* (where women are encouraged to relinquish their share of inheritance to their brothers to maintain good family relationships and be allowed their traditional visits home to see their family when they are married) mean landownership by women remains low. The BIHS shows that 86% of plots are owned by men, 12% by women, and 2% jointly, and that plots owned by women are significantly smaller than those owned by men or jointly (Kieran et al., 2015). Further, women tend not to work in the paddy fields, instead focusing on homestead-based processing activities (Headey & Hoddinott, 2016). Indeed, social customs often limit women's movements, for example, some women are reportedly unable to access drinking water deemed arsenic-safe if there is none available within a permitted distance of the homestead (Sultana, 2008). The work that NGOs are doing is making some progress in advancing women's rights (Kabeer (2011)), but the coincidence of gender-based and ownership-based marginalization serves to highlight the complicated relationship between the rice agriculture and socioeconomic systems.

Indeed, further highlighting such relationships, Majumder et al. (2016) found that the determinants of technical efficiency in rice farming in Bangladesh are farm size; farmer's level of education; experience in production; and access to microcredit, training, and extension. However, Islam (2015) describes the diverse impacts of microcredit programs, while Paprocki (2016) notes the limitations of microcredit for agricultural improvement: "The lack of support of microcredit programs for smallholder agriculture is apparent in the repayment structure, which requires borrowers to begin making payments on their loans the week immediately after borrowing. This structure is common to every major NGO microcredit program in Bangladesh." This means that microcredit is not suitable for investments, such as buying land, where rewards will not be seen until the harvest. Further, while extension workers can teach about high-yielding varieties, modern agricultural inputs, and irrigation, and Majumder et al. (2016) found a significant improvement in the *boro* yields of farmers who had training from extension workers, the impact of extension workers is still relatively low. In one study, only 9% of 6,500 farmers reported that they had been in contact with an extension worker in the previous 12 months (Ahmed et al., 2013).

## 3 | ALTERNATE WETTING AND DRYING

Rice evolved from a semiaquatic ancestor, which means it can thrive in flooded conditions when most other plants (such as weeds) cannot. As a result, rice has traditionally been grown in flooded fields. In this process, lowland rice fields are prepared for the transplantation of seedlings by soaking, ploughing, and puddling. Puddling is the term used to describe rotovating or harrowing under shallow submerged conditions, which helps to control weeds, reduce soil permeability, and ease transplanting. After the field is prepared, it is usually left flooded for anything from a few days to four weeks before the seedlings are transplanted. A cross section through a typical paddy field would show 0–20 cm of ponded (standing) water, a puddled muddy topsoil of 10–20 cm, and then a threshold known as the plough pan on top of solid, undisturbed subsoil. The plough pan is formed by decades or centuries of puddling for rice cultivation, and the rice roots tend to be restricted to the puddled region of soil above the compacted plough pan (Bouman, Lampayan, & Tuong, 2007; Price et al., 2013). A unique feature of this flooded system is the ability to grow the same crop on the same land season after season, probably because the flooding reduces the build-up of antagonistic micro- and macroorganisms. These pests and diseases are the main reason why aerobic crops have to be rotated.

The agricultural system described above uses a lot of water. Indeed, rice has the highest water need of any arable crop, and acute water shortages in rice-growing areas have led to people looking for more sustainable cultivation methods (Datta, Ullah, & Ferdous, 2017). A report from the International Water Management Institute (Amarasinghe, Sharma, Muthuwatta, & Khan, 2014) predicting how Bangladesh could meet its increasing rice demand to 2030 suggested groundwater consumption from irrigation alone could exceed aquifer recharge, and in some districts, this is already the case, meaning there is a strong imperative to increase the water productivity of rice production. The report notes the potential of "deficit irrigation" in Boro season rice. AWD is a deficit irrigation method whereby, as noted above, the soil is allowed to dry out for a period of one to several days after the ponded water has disappeared, before being re-flooded (Lampayan, Rejesus, et al., 2015). During this period, although no standing water can be seen in the field, the roots of rice plants are still adequately provided with water (Rejesus, Palis, Rodriguez, Lampayan, & Bouman, 2011). Variations of AWD are also sometimes known by other names such as "controlled irrigation" and "multiple irrigation" depending on the country and the research context (Adhya et al., 2015). Mid-season drying of paddy fields has been practiced in Japanese rice cultivation for over 300 years as it is thought to increase yields (van der Hoek et al., 2001), and cycles of wetting and drying were first proposed as a potential technique to reduce populations of human disease vectors in the early 20th century (van der Hoek et al., 2001). However, the development of AWD as a precise farming practice for water saving is more recent.

The phrase "safe" AWD was coined by Bouman et al. (2007). They developed a "field water tube," also known as a "pani pipe" which is a piece of pipe with small holes made in it which is inserted into the ground and the earth removed from within it. This allows the farmer to see the depth of the water under the soil surface. Safe AWD dictates that when the water level reaches 15 cm below the soil surface, the field should be re-flooded to a depth of 5 cm. As long as the water level is not allowed to drop below 15 cm below the soil surface, the rice roots remain wet and no yield penalty is observed (Bouman et al., 2007). The length of time after transplanting that AWD is started differs between authors. Bouman et al. (2007) consider it safe to start AWD after "a few days," but other authors report maintaining standing water for 10 (Li & Li, 2010), 21 (Lampayan et al., 2015), or even 28 days (Oliver, Talukder, & Ahmed, 2008). The decision over when to start AWD will significantly impact the water saving achieved by the practice, but the literature is not yet decided on a definite answer. It is also unclear as yet what this standing water is for, whether it is to reduce weeds (Rahman & Bulbul, 2014), to aid crop establishment (Lampayan, Samoy-Pascual, et al., 2015), to ensure maximum nitrogen uptake before water is allowed to drain (Linquist et al., 2015), or perhaps a combination of these factors.

"Safe" AWD also includes keeping ponded water on the field for 2 weeks around flowering, as this is when the crop is most susceptible to drought (Bouman et al., 2007). However, in their meta-analysis of 56 studies, Carrijo, Lundy, and Linquist (2017) found that mild (or "safe") AWD practiced either during the vegetative stage or the reproductive phase did not affect yield, and there was only a yield reduction of 8.1% if AWD was practiced continuously through the season. This study also highlighted the importance of the soil physical and chemical properties in maintenance of yield under AWD. For example, when AWD was practiced in acidic soils (pH < 7), the average relative reduction yield was 5.3%, whereas average yield was reduced by 18.7% when AWD was applied on soils with pH ≥ 7 (Carrijo et al., 2017). In addition to pH, the soil organic content also had an impact on the yield response of plants grown under AWD, with those grown on soils with a high (>1%) soil organic content performing better (only a 4.3% reduction in yield) compared to those grown on soils with a lower soil organic content (11.6% reduction in yield) (Carrijo et al., 2017). Such observations are very important when considering the adoption of AWD on a national scale, as soil properties can differ between regions and within regions (Chowdhury et al., 2017).

Once farmers are comfortable using AWD and the soil water tube, it is argued, they may wish to experiment by lowering the threshold level for irrigation, and it is suggested that at times of water shortage or high water prices, some yield penalty may be acceptable (Bouman et al., 2007). Fully aerobic rice cannot be repeat cropped on the same piece of ground year on year without a yield reduction, but this is not a problem with rice fields cultivated under AWD (Bouman et al., 2007).

Studies examining AWD report a range of impacts, from severe yield declines to yield increases, and a range of values for volume of water saved. These discrepancies may be attributed to differences in soil conditions, irrigation method applied, and the season studied (Yang, Zhou, & Zhang, 2017). Carrijo et al. (2017) reported that "mild" AWD did not reduce yield under any soil properties or management practices, but yield losses under "severe" AWD were 22.6%, although this analysis did not distinguish between rice cultivation seasons. This supports the conclusion that "safe" AWD can be practiced without concern for yield loss. Although "safe" AWD specifically states that irrigation should not be restricted during flowering, in their review paper, Yang et al. (2017) report an increased grain yield of 6.1%–15.2%, a reduction in irrigation water of 23.4%–42.6%, and an increases in water productivity of between 27% and 51%, despite AWD taking place throughout the growing season.

In addition, it has been shown that AWD can effectively decrease water inputs by 15%–30% (Bouman et al., 2007) with Carrijo et al. (2017) finding that "mild" AWD can reduce water use by 23.4%. On-farm trials in Bangladesh suggested that the potential water saving may be as high as 38% without reducing yields (Lampayan, Rejesus, et al., 2015). AWD increases water-use efficiency at the field level which is thought to be through reductions in the percolation and seepage rates, rather than through reductions in evaporation (Bouman et al., 2007; Oliver et al., 2008). Howell, Shrestha, and Dodd (2015) found that although effective tiller number and yield were not significantly different between AWD and control treatments, water-use efficiency was 133% higher under AWD. Water-use efficiency in AWD may be increased even further by keeping seedlings in nursery beds for longer. In 2010, seedlings transplanted after 21 days had a higher yield than seedlings transplanted after 14 days as well as an 11% reduction in water usage (Lampayan, Samoy-Pascual, et al., 2015). Seedlings transplanted at 30 days gave an 18% reduction in water usage but yield was lower than 14- or 21-day-old seedlings. Interestingly, no significant difference was found in yield between seedlings transplanted at 14 or 21 days in 2011, and there was no significant difference in water application, thought to be due to rainfall early in the season (Lampayan, Samoy-Pascual, et al., 2015).

But water saving is not the only benefit of AWD. As arsenic is most available to rice plants under anaerobic conditions, it follows that reducing the length of time the rice is growing anaerobically may reduce the uptake of arsenic (Brammer, 2008). A reduction in rice grain arsenic in plant grown under AWD compared to grain arsenic in plants grown under continually flooded condition has been observed in a number of studies (Chou et al., 2016; Linquist et al., 2015; Somenahally, Hollister, Yan, Gentry, & Leoppert, 2011). In the most recent Bangladesh study, Norton et al. (2017) reported a decrease in arsenic concentration of 24% in shoots of rice plants grown under an AWD regime and a decrease in grain arsenic of 14% and 26% for each of 2 years.

Further, as well as having a detrimental effect on aquifers, pumping water is energy intensive (Nelson, Wassmann, Sander, & Palao, 2015). Rejesus et al. (2011) found that adopters of AWD in Tarlac province in the Philippines used 25 hr less irrigation than non-adopters, which amounted to a total reduction of 38%. In this area, households have access to a pump once per week and those practicing AWD appeared to use the pump as often as non-adopters, just not for as long. In the study area, farmers must provide their own diesel to run the pump, and this translated to a monetary saving for the household (Rejesus et al., 2011).

Finally, in paddy fields, as in any wetland, standing water stops oxygen from reaching the soil and anaerobic decomposition of organic matter releases methane and to a lesser extent nitrous oxide (Richards & Sander, 2014). Estimations of annual emissions from paddy fields range from 500 million tonnes to 800 million tonnes of carbon dioxide equivalent, and 15–100 million tonnes of carbon dioxide equivalent from nitrous oxide (Adhya et al., 2015). While there is a consensus that AWD can reduce methane emissions from paddy fields, it is known that aerobic rice production increases nitrous oxide emissions. It is thought, however, that the reduction in methane emissions achieved by AWD far outweighs the additional nitrous oxide emissions produced (Adhya et al., 2015). For example, in Arkansas, Linquist et al. (2015) reported a 48% decrease in methane emissions from their less severe AWD treatment, and an overall reduction of 45% in greenhouse gas (GHG) emissions when the increase in nitrous oxide was taken into account.

Bangladesh is a signatory of the Paris Climate Agreement, and as such has committed to curbing its GHG emissions. As rice production is a large contributor to Bangladesh's emissions, AWD presents a good opportunity to help address its emissions targets.

Various bodies within Bangladesh have been trialing and promoting AWD. Field trials were carried out at the BRRI sites at Gazipur (Islam et al., 2016; Paul, Rachid, & Paul, 2013; Rahman & Bulbul, 2014) and Bhanga (Rahman, Islam, Hassan, Islam, & Zaman, 2014) as well as at the Bangladesh Agricultural University farm at Mymensingh (Norton, Shafaei, et al., 2017; Oliver et al., 2008), and Lampayan, Rejesus, et al. (2015) reported a summary of unpublished results from farmer-participatory demonstration sites. Various experiments have reported water saving in AWD plots of 20% (Oliver et al., 2008; Paul et al., 2013), while Rahman and Bulbul (2014) found that all of the AWD treatments significantly increased yield when compared to the standing water control plots. This contrasts, however, with Oliver et al. (2008) who found that all AWD treatments significantly reduced yield (6.86 tonnes/ha in control conditions, 5.86–6.58 tonnes/ha under varying AWD treatments), while Paul et al. (2013) found that yields under AWD (where water level reached 15 cm below ground level) were slightly higher than the standing water control over years (5.9 and 5.7 tonnes/ha in 2011 and 6.2 and 6 tonnes/ha in 2010), but that the further two AWD treatments (where water level reached 20 and 50 cm below ground level) gave yields lower than the standing water control.

Four other studies conducted in Bangladesh only compared a standing water control to one AWD treatment, allowing the water to drop to 15 cm below the soil surface as in "safe" AWD (Bouman et al., 2007). Islam et al. (2016) found that AWD significantly increased yield by 16% in 2010 but had no significant effect on yield in 2011. Rahman et al. (2014) reported no significant difference in yield, with reported values of 6.33 tonnes/ha for AWD plots and 5.51 tonees/ha for control plots. Norton, Shafaei, et al. (2017) reported AWD caused a significant average grain mass increase of 9.8% and 9% compared to continually flooded over their two-study years. Another study by the same authors (Norton et al., 2017) testing AWD on 22 cultivars in three sites in 2014 found AWD increased yield overall by 6.5% with individual site increases of 18.4% in Mymensingh, 8.7% in Madhupur, and no difference in Rajshahi. Oliver et al. (2008) were the only authors to report a reduction in grain yield in Bangladesh, and the results from all of the other authors suggested that AWD, particularly "safe" AWD, will either maintain or slightly increase rice yields in Bangladesh. This is supported by the results reported by Lampayan, Rejesus, et al. (2015) for farmer-participatory AWD demonstration sites where AWD increased yield by between 0.4 and 1 tonnes/ha compared to normal farmer practice.

Several authors explored the effect of AWD on yield-contributing factors to analyze what plant physiological changes may underlie any change in yield. Two authors found that AWD increased the number of productive tillers per plant or hill (Norton, Shafaei, et al., 2017; Rahman & Bulbul, 2014) but whereas Rahman and Bulbul (2014) found that the total number of tillers increased, Norton, Shafaei, et al. (2017) found that only the number of productive tillers increased. In contrast, Oliver et al. (2008) found that AWD reduced the number of effective tillers per hill, without having a significant effect on the total number of tillers per hill or the number of non-effective tillers per hill. This is perhaps unsurprising given their finding of reduced yield in AWD plots. As well as disagreeing over the effect on tiller production, the other yield-contributing factor results of Rahman and Bulbul (2014) appear as the opposite of Oliver et al. (2008) with Rahman and Bulbul (2014) reporting that AWD also increased the filled grains per panicle, thousand grain weight, grain yield, straw yield, and biological yield. Oliver et al. (2008) report that AWD causes a decrease in the number of filled grains per panicle, the number of spikelets per panicle, grain yield, straw yield, and dry matter yield. Importantly, both authors agree that AWD increases the harvest index; an observation was also made by Norton, Travis, et al. (2017).

Some authors combined their study of the effects of AWD with other factors. Norton, Shafaei, et al. (2017), for example, looked at the effect of AWD on plant hormone levels and reported subtle yet significant effects. Rahman et al. (2014), Norton, Shafaei, et al. (2017), Norton, Travis, et al.

(2017) found that grain arsenic concentration is significantly lower in plots irrigated using AWD without reducing yield, although Norton, Shafaei, et al. (2017), Norton, Travis, et al. (2017) caution that as AWD irrigation can increase grain cadmium levels and decrease grain iron levels. Consideration of these additional impacts is required when considering adopting AWD. These results show that the relationship between AWD and numerous factors influencing rice yield and nutrition is as complicated in the Bangladesh setting as they are worldwide.

Despite the positive outcomes of studies on AWD in Bangladesh, as summarized above, there are no reports of AWD being adopted by farmers in the country. Importantly, the implication that AWD is not being adopted was backed up by anecdotal evidence the authors received while discussing AWD with many actors (including IRRI Bangladesh, BRRI, BRAC, the Rural Development Academy and scientist from Bangladesh Agricultural University, and Dhaka University) during a visit to Bangladesh in November 2017. The situation in Bangladesh appears to contrast with that in the Philippines and China, where it seems to have been more easily accepted by farmers. In the Philippines, for example, The Bohol irrigation system consists of three interdependent dams and canal systems. Farmers at the end of the irrigation system often experienced unreliable water supply, so in 2006, a revised irrigation schedule was introduced which forced farmers to allow their fields to dry out between irrigations (Valdivia et al., 2015). Valdivia et al. (2015) interviewed upstream and downstream farmers in 2005 before the new system was introduced, and in 2010 to review its effectiveness and found that the introduction of the new irrigation regime reduced the inequality in yield between upstream and downstream farmers. In 2005, the average yields were 2.92 and 2.47 tonnes/ha, respectively, and in 2010, yields were 3.18 and 3.16 tonnes/ha (Valdivia et al., 2015). Additionally, the introduction of more reliable irrigation allowed the dry season rice area to increase by 16%, the majority of which was in the downstream area (Valdivia et al., 2015). This increased the cropping intensity of the area from 119% to 160% (Siopongco, Wassmann, & Sander, 2013). China too has had success with the introduction of AWD. For example, Yulin Prefecture statistics suggest that water-saving irrigation has been adopted in 30,000 ha of rice-growing land, with the annual water saving estimated at 100 million $m^3$ (Mao Zhi, 1996 in van der Hoek et al., 2001). While Li and Barker (2004) identified a number of bio-physical and socio-economic constraints to the adoption of AWD, they also reported that by 2002 AWD had been applied to 40% of the rice production area across China (or 12 million ha) (Li & Barker, 2004; MWR 2003). The high degree of adoption of AWD in China was accompanied by a number of incentives, including volumetric water pricing and water-use associations (Li & Barker, 2004). An important study on AWD was conducted in Nepal by Howell et al. (2015) combining agronomy with social science research. There they found good agronomic reasons to adopt AWD (especially water saving) but suggested it was unlikely to be adopted because of issues related to reliable access to irrigation (at the right time) and limited economic incentive for the individual farmer. Might this also be the case in Bangladesh?

## 4 | CHALLENGES TO ADOPTION OF AWD IN BANGLADESH

There are two social science studies looking at the uptake and impact of AWD in Bangladesh, although both are limited and examine only impacts from controlled studies. In their study, Kurschner et al. (2010) report that 81% of 96 farmers who had implemented AWD had perceived yield increases from using AWD. Rahman (2016) too reports that from farmers interviewed in five villages, yield increase was reported as a positive impact of AWD adoption. While both of these studies also recognized some negative aspects of adopting AWD (primarily weeding), the studies provide no substantial assessment of the socioeconomic dynamics of AWD as a farming practice.

However, using other cases, we can gain some indications of pertinent socioeconomic dynamics.

In the two cases of success noted above (the Philippines and China), and in that of the USA (Nalley, Linquist, Kovacs, & Anders, 2015), socioeconomic dynamics served to encourage the adoption of AWD as an innovative farming system. In the Philippines, 86% of irrigation comes from surface water and farms at the end of canal irrigation systems often face unreliable water supply and seasonal shortages (Adhya et al., 2015). In canal-based systems, therefore, the incentive to adopt water-saving irrigation generally has to come from the irrigation authority in an imposed manner, for example, enforced intermittent irrigation as was introduced to Bohol Island (Richards & Sander, 2014; Valdivia et al., 2015). Recently, however, the Philippines has seen an increase in privately owned pump irrigation from groundwater due to increased water shortages and the availability of cheap pumps. Pumps are most common at the end of canal irrigation systems, and about 25% of farmers are thought to have some access to groundwater irrigation (Adhya et al., 2015). Farmers who control pumps, therefore, see a financial benefit from the adoption of AWD, as it is common for farmers to have to provide their own diesel for running the pump (Richards & Sander, 2014). In China, the introduction of volumetric charges for water use—the benefits of which also accrue to the individual farmer—has similarly contributed the uptake of AWD (Li & Barker, 2004; van der Hoek et al., 2001).

Although green revolution technologies have vastly improved harvests in Bangladesh, some feel that the monetary benefits have not been realized by poor households as hikes in land rent and irrigation charges allowed the wealthier sections of the peasantry to siphon off the productivity gains brought by the technology (Adnan, 2007). Deep tubewells, for example, are largely owned by wealthier farmers who then benefit from their control of water distribution to their neighbors. However, other authors argue that, for water in particular, this does not hold true as the introduction of shallow tubewells has helped to break the monopoly of access to irrigation water-rich landowners previously held (Hossain, 2009). Bell et al. (2015) found that plots managed by farmers who rent their access to irrigation infrastructure perform no worse than the plots of farmers who own their own infrastructure, which they interpret to mean that ample groundwater facilitates informal markets which act to improve access and equity for irrigating farmers.

Such markets for irrigation water, as described by Hossain (2009), include several possible modes of payment for water access. These include sharing a quarter of the harvest with the tubewell owner, a flat charge per area paid in cash installments over the season, or an hourly rate for renting the machine with the tariff accounting for the source of fuel. However, contrary to the fuel savings experienced due to less water use in the Philippines and the volumetric-based charge for irrigation water which incentivize less water use in the case of China, and in Bangladesh, most irrigation water is paid for not per volume but per hectare of land irrigated. As a result, there is no benefit directly to the farmer for using less water and so no incentive to do so. Some studies have shown that efforts to encourage AWD must overcome this incentivization problem.

Working in a village near Khulna, for example, the USAID-funded Cereal Systems Initiative for South Asia negotiated a fixed hourly rate for pump use with tubewell owners (Lampayan, Rejesus, et al., 2015). This allowed farmers to see financial benefit from reducing their water usage, and it was beneficial for the pump owners too as they could sell water to more farmers. The successful system was copied by tubewell owners in two neighboring villages (quoted in Lampayan, Rejesus, et al. (2015) as personal correspondence with T. Russell). Lampayan, Rejesus, et al. (2015) also reported the less successful effort to arrange volumetric pricing undertaken by Rangpur and Dinajpur Rural Services (RDRS). RDRS tried to organize farmers and influence pump owners, but found pump owners unwilling to change, particularly those benefitting from subsidized electricity. Lampayan, Rejesus, et al. (2015) note that the varying success of these two projects reflects the lack of a national level strategy, with some organizations reporting local successes but no framework to expand these into regional or national campaigns.

Another hint as to the pertinent socioeconomic dynamics from the case of China regards conflicts arising from the sharing of resources. In a Chinese case regarding the farmer uptake of a drip irrigation model, for example, and as reported by Burnham, Ma, and Zhu (2014), conflicts arose for a number of reasons. The decision to irrigate had to be made communally, and this was difficult as the farmers often grew crops with different water requirements. Fertilizer was added to the drip irrigation system, and farmers believed that those with plots closer to the irrigation source were getting a larger share of this joint resource. Finally, some of the farmers did not fully understand the theory of drip irrigation and worried that without visible moisture on the soil surface their crops were not getting enough water. This resulted in people manipulating the system by either cutting extra holes in the tubing or disconnecting the lines at night to irrigate their fields. These results support the findings of Blanke, Rozelle, Lohmar, Wang, and Huang (2007) that farmers have a strong preference for individual agriculture management practices where technologies do not need to be shared, with some stating that they would be happy to use drip irrigation if they had their own system.

Although unwillingness to use communal resources in China may partially be a legacy of collective farms, there is no reason to assume that such similar dynamics will not be apparent in other settings. Indeed, conflict with those sharing equipment may be one of the biggest barriers to uptake of AWD, as farmers must coordinate cropping to also coordinate irrigation needs. In short, while there are many reasons to believe that AWD would benefit the rice agriculture system in Bangladesh, there are also quite clear reasons why its adoption would be limited in the prevailing socioeconomic system. Indeed, the obvious barriers raised by lack of economic incentives for individual farmers and the potential conflict over resources, even amid the sparsity of social science research into the connection between the agricultural system and the socioeconomic system, should make clear that even more socioeconomic barriers remain hidden from view. Further examination of the relationship between these systems is clearly necessary if AWD is to be encouraged and promoted as a solution to the issues of water degradation, arsenic poisoning, and methane emissions.

## 5 | CONCLUSION

The purpose of this article has been to review the literature pertinent to the adoption of Alternate Wetting and Drying for rice cultivation in the case of Bangladesh as an example of the complex relationship between the biology and socioeconomics of agriculture as it relates to water saving in irrigation. In meeting this end, the paper necessarily also reviewed literature on the rice agriculture system in Bangladesh, the purported benefits of AWD, and the observed socioeconomic dynamics of its adoption in other cases. In presenting this literature (the latter of which is extremely limited), it has become clear that while AWD appears to be a technique that has agronomic benefits, there are many unanswered questions regarding AWD as an element of an agricultural system (what are the mechanisms exactly which connect aerobic cultivation to less arsenic or more yield, and what specific soil and environmental factors limit or enhance these effects?), there are just as many questions altogether unexamined regarding the socioeconomic system into which it must be inserted and with which it must interact. While this study is focused on Bangladesh, key constraints to the implementation of AWD, for example, water availability and water pricing, as well as strategies to overcome these constraints (e.g., incentivization), are likely to be common to many countries and regions.

The key questions that future research must examine, therefore, are as much about the relationship and interaction between the agricultural and socioeconomic system as they are about either of those systems independently. As such, addressing the challenges posed by the failure to adopt AWD in the case of Bangladesh over the past decade demands a holistic and interdisciplinary endeavor which can knit together the agronomic and the economic, the biological, and the social. To meet global food security, it is going to require biological / agronomic improvements in crop production as well as understanding how this improved system can be implemented and adopted at a large scale. To date, the research on AWD in Bangladesh has largely failed to produce a synthesis of these approaches and, as a result, has failed to articulate a suitable strategy or policy by which AWD may be encouraged and incentivized among farmers. This is the challenge that must be met if the apparent benefits of AWD as a farming practice are ever to be experienced in the case of Bangladesh.

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## ORCID

*Gareth J. Norton* http://orcid.org/0000-0003-4560-170X
*Adam H. Price* http://orcid.org/0000-0003-3094-0485

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