Climate-smart irrigation and responsible innovation in South Asia : A systematic mapping

Ambio

Prutzer, Edward; Patrick, Anne; Ishtiaque, Asif; Vij, Sumit; Stock, Ryan et al

https://doi.org/10.1007/s13280-023-01895-4

Ambio
https://doi.org/10.1007/s13280-023-01895-4

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

REVIEW

Climate-smart irrigation and responsible innovation in South Asia: A systematic mapping

Edward Prutzer, Anne Patrick, Asif Ishtiaque, Sumit Vij, Ryan Stock, Maaz Gardezi

Received: 16 December 2022 / Revised: 15 April 2023 / Accepted: 7 June 2023

Abstract This review systematically traces the context and evolution of climate-smart irrigation (CSI) in four South Asian countries—Bangladesh, India, Nepal, and Pakistan. CSI technologies and practices strive to address two main objectives: (1) sustainably enhance agricultural/water productivity and rural farm incomes to build community and farm-level resilience to climate change and (2) enable adaptation/mitigation to climate change across different scales through irrigation technologies and water resources management. These innovations also pose various social and environmental challenges. This review extracts findings from existing literature related to potential societal and environmental benefits and risks associated with CSI and outlines opportunities for responsible innovation to elaborate robust and democratic roles of CSI technology and engender equitable technological change. We identify three drivers (climate variability and GHG mitigation, cost savings and support structure, and water conservation and management) and five barriers (financial support, high initial cost, inadequate practice-based research, lack of knowledge and/or access, and structures of power).

Keywords Climate-smart agriculture · Climate-smart irrigation · Precision irrigation · Solar pumps · South Asia · Water policy

INTRODUCTION

South Asia faces an urgent need for sustainable water and agricultural practices given the heightened effect of escalating drought and flood risks in the region (Khatri-Chhetri and Aggarwal 2017; IPCC 2021). In 2022 alone, floods in Pakistan displaced 33 million people and damaged property in excess of $30 billion (New York Times 2022). Many of those who were displaced by the floods are dependent on small-scale crop and livestock farming for their income and food security. Overall, South Asia as a region has high economic dependence on agriculture and faces wide-scale food insecurity and malnourishment that particularly impacts women and youth (Aggarwal 2015). Given the magnitude and severity of climate change-driven impacts, organizations like the Asian Development Bank (Ahmed and Suphachalasai 2014) and the World Bank (Agarwal et al. 2021) identify that through innovative climate-smart technologies and policies, countries in the Global South may be able to address the grand challenges of the twenty-first century. Climate-smart irrigation (CSI), as a proposed innovation to address this global sustainability challenge, carries potential to increase agricultural production while conserving soil and water resources in this region. CSI technologies use localized weather and soil moisture data to allow farmers, water managers, and regulators to make improved irrigation management decisions. CSI includes both analog and digital irrigation technologies and practices to tackle two main objectives: (a) sustainably enhance agricultural productivity, water productivity, and rural farm incomes to build community and farm-level resilience and climate change, and (b) enable adaptation, mitigation and resilience to climate change across different scales through irrigation technologies and water resources management (Goap et al. 2018). CSI technologies can use

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13280-023-01895-4.

Published online: 14 July 2023

localized data to allow farmers, water managers, and regulators to make improved irrigation management decisions (Taneja et al. 2019).

While challenges in CSI management are place-specific (Molle 2003), from the 1980s onward, groundwater pumps have played a significant role in South Asia for irrigation. Proliferation is in large part due to technological advances in micro-irrigation which have come with decreases in size and price (Barker and Molle 2004). Use of tubewells grew particularly prominent in India and Pakistan, part of a broader trend in Asian metropolitan areas (Foster et al. 1998). Since 2011, scholarly writing on CSI has generally become more diverse vis-à-vis inclusion of a broader range of technologies.

Researchers, nation states, and non-governmental organizations (NGOs) herald CSI's potential to bolster sustainable agriculture if successfully adopted by smallholder farmers (Shilomboleni 2020). However, concerns remain about low levels of use of CSI among farmers in South Asia; socioeconomic status is a major determinant to CSI adoption, as these technologies are quite expensive to implement and maintain. These innovations also pose various social and environmental challenges. For instance, solar irrigation pumps can enable both the mitigation of climate change and adaptation of vulnerable farmers, but may inadvertently exacerbate over-extraction of groundwater, thereby entrenching existing inequalities and injustices related to water access (Closas and Rap 2017; Wong 2019). It is important, therefore, to examine possibilities by which inclusive modes of innovation governance can steer CSI technologies and practices to socially and environmentally responsible and adaptive outcomes.

Recent research in responsible innovation (RI) builds on studies of controversies surrounding emerging technologies and provides insight into deep uncertainty and knowledge asymmetry associated with the future social implications of technologies. RI postulates that research and innovation should be attuned to societal needs. Specifically, through meaningful engagement with a range of stakeholders and decision-makers in the 'upstream' or early stages of technology development, RI aspires to enable emerging technologies to become mutually responsible and responsive to environmental changes and social and political demands (Stilgoe et al. 2013; Von Schomberg 2013; Gardezi et al. 2022). As a development approach to new technologies, in recent years, the RI framework has been applied to investigate the innovation processes of several emerging technologies, such as nanotechnology (Fisher and Rip 2013), geoengineering (Stilgoe et al. 2013), synthetic biology (Tucker and Zilinskas 2006), and precision agriculture (Gardezi et al. 2022).

Given RI's limited current application toward new technologies in agriculture in South Asia, and for addressing challenges of sustainability (L'Astorina et al. 2015; Bogner and Torgersen 2018; Pant 2019; Frankelius et al. 2019; Barrett and Rose 2020; Klerkx and Rose 2020; Mamidipudi and Frahm 2020; Tricarico et al. 2020; Simelton and McCampbell 2021), there is a need for full consideration of the social and ethical implications of CSI's implementation. Furthermore, how CSI technologies are coming into practices in the Global South and the barriers and challenges associated with CSI adoption are little documented.

Against this background, this paper contributes to the gap in existing research on responsible innovation of emerging agricultural technologies in the Global South. This paper uses a systematic mapping (SM) to specifically trace the context and evolution of CSI in four South Asian countries—Bangladesh, India, Nepal, and Pakistan. Our research questions are as follows: *(1) How have innovations in CSI technologies evolved in South Asia between 2011 and 2021?; (2) What have been the drivers of and barriers to CSI adoption and implementation during that time?; (3) What country-specific outcomes (positive and negative) have come from CSI use?* Overall, our study focuses on the evolution, drivers, barriers, and regional outcomes of CSI. In the following sections, we first overview our methodological approach (Section "Method"), then describe our findings (Section "Results"), and explain the relevance of our findings for South Asia (Section "Discussion"). Lastly, we conclude our study and discuss new avenues for future research (Section "Conclusion").

METHOD

Rationale for systematic mapping

SM allows us to assess where the existing literature is already robust and, by proxy, what scholarship needs further exploration on the barriers and drivers of CSI in South Asia. We saw specific potential in a SM to investigate societal and environmental implications of emerging CSI technologies by subjecting existing literature to a critical sociotechnical analysis. Our mapping followed the ROSES protocol (RepOrting standards for Systematic Evidence Synthesis in environmental research), a systematic approach with particular salience toward topics of social and environmental sustainability (Haddaway and Macura 2018). The ROSES protocol—while translatable to various topics and disciplines—was built to address such questions and thus warrants use here (ROSES 2017). The next subsection details the steps of the SM following this protocol.

Data collection and screening

To start, the SM included six search queries (detailed in supplementary protocol document) that were run within two database collections: (a) Scopus and (b) Web of Science. Scholarly appraisal of the fit of these databases within the environmental sciences informed the selection of these two databases (Vij et al. 2021). The design of the six queries among the co-authors was carefully considered for aggregating all search results that could carry potential relevance under the scope of our research questions. Though one can find more detail in our supplementary material, in addressing CSI, articles had to refer to technological innovations aiding irrigation practices and being implemented with the intent to combat food insecurity and/or advance sustainability. By sustainability, we refer to agricultural and food system advancements that balance the needs of economic systems, ecosystems, stakeholders, and societies (USDA 2011).

Next, the authors collaborated to screen articles based on their titles, abstracts, and keywords. Our initial body of literature included 2085 results from Scopus and 3053 results from Web of Science. Our article list (n = 3282) to begin reviewing was finalized following removal of duplicates (n = 1411). Our inclusion/exclusion criteria stipulated that articles must (1) focus on one of four South Asian countries (Bangladesh, India, Nepal, and Pakistan); (2) focus on a technology that falls under CSI (i.e., solar pumps, drip irrigation, precision agriculture, drones, satellite images, laser land leveling, wind pumps, and nutrient management); and (3) apply discussions of CSI technology to advance sustainability (be it in the reduction of greenhouse gas emissions or other environmental footprints of agriculture practice that could prove harmful to the environment). Studies had to meet all three criteria to be included in the SM. For instance, articles that focused on solar technology as applied to agriculture in India, but for purposes of heating crops rather than for irrigation were excluded.

Other common themes among excluded articles included use of solar technologies in the countries of focus in terms of sustainable energy systems but not irrigation practice, CSI implementation outside the study region, and implementation of climate-smart technologies not explicitly geared toward irrigation. To bound the scope of our mapping for richer comparative analysis, we focus on the Hindu Kush Himalayas specifically rather than South Asia broadly. We define the Hindu Kush Himalayas through four specific South Asian countries—Bangladesh, India, Nepal, and Pakistan. In the corpus of literature our search queries yielded, research focusing on other South Asian countries (Afghanistan, Bhutan, Sri Lanka, and the Maldives) was excluded. Our focus on Bangladesh, India, Nepal, and Pakistan specifically emanates from their high ranking for South Asian countries most impacted at this time by climate change, changes in monsoon patterns, and accelerated glacial melting, and where stakes are high in terms of the large portion of national GDP generated by agriculture (Khatri-Chhetri and Aggarwal 2017). The four countries are home to about 2 billion people, which constitutes a quarter of the world population (Khatri-Chhetri and Aggarwal 2017), with high levels of poverty and dependence on agrarian livelihoods. As such, the proliferation of CSI is occurring in the context of food and water insecurities in the region, both of which are becoming more acute because of the climate crisis.

Lastly, full-text review, critical appraisal, and extraction were split between the co-authors. 2952 articles were excluded at the former step, with 210 additional removed articles at full-text review. Both stages employed the three aforementioned criteria for advancement. 26 articles did not meet the criteria our team set for critical appraisal. As part of our critical appraisal, we looked for specific explanations of methods. This removed, for instance, broad literature reviews that did not specify precisely how the review was conducted or pieces that were more editorial in nature rather than statistical or case-based research.

Analytic approach

Data extracted from each of the 79 articles analyzed included but were not limited to CSI technologies mentioned; discussions of drivers and risks cited in implementation; barriers to adoption; challenges in governance and management mentioned; discussions of race, class, gender, and caste in adoption; development goals mentioned; and countries of focus in the mapped research. We combined deductive and inductive coding approaches following extraction, which is when the first author also coded for each theme explored in our Results section based on the co-authors' findings. Themes emerged from the ground up with the co-authors' assessment of how mapped literature addressed categories included in the extraction table.

Initial categories were based on operational definitions of drivers and barriers in RI literature, including categories of social difference (race, class, caste, gender, and place) that factor into local and regional technology adoption. We then used inductive analysis to identify key phrases and insights from the literature to forge links back to operational definitions of drivers and barriers. This approach, endorsed by Bingham and Witkowsky (2022), then builds the central points of our results and discussion sections.

Our coding of drivers and barriers comes from operational definitions in RI literature. In categorizing drivers from our corpus of literature, we aim to identify frequently discussed building blocks which move the needle for CSI implementation, innovation, and adoption. By invoking barriers, we pinpoint what authors describe as prohibiting uptake of CSI practices and associated technologies (Thapa et al. 2019).

Limitations

Our focus on peer-reviewed journal publications ensured sufficient scholarly vigor and appraisal to articles included in our mapping. It may, however, exclude relevant conference papers and book chapters that may have received a similarly high degree of vetting. Our final database constituted a corpus of research written and published in English. These decisions were necessary for reasons of practicality and out of adopting a commonly accepted scholarly standard that could be used to narrow the initial corpus of literature to the most pertinent results.

In addition, given that most CSI research thus far has mainly focused on solar irrigation pumps, our search queries often incorporated terms like "solar pump," "solar irrigation," and "solar technology." We did have a broad search query meant to fetch all articles with the terms "climate-smart" and "agriculture" within our publication span, and in search queries using terms focused on solar, we also incorporated "precision irrigation" as a broader search term. With that said, we recognize our decisions may have skewed toward solar applications.

We acknowledge that our use of "climate-smart" may exclude some relevant literature on techniques more often described as "climate-resilient" instead such as use of farm ponds and other initiatives pushed under climate-resilient agriculture We must also note that the relevant literature can treat CSI and climate-smart agriculture (CSA) as synonymous. While our inclusion/exclusion criteria mandated applications to irrigation specifically, we realize that the inextricable treatment of these two terms may mean some discussions we collected intended to reference a broader suite of applications under CSA rather than the particular challenges of CSI (Fig. 1).

RESULTS

Evolution and trends in CSI in South Asia

We organized our results to document technologies identified and discussed (as shown in Table 1). We specifically examined the growth of relevant literature between 2011 and 2021, drivers and barriers most commonly cited in the literature, and a summary of findings organized by country. Discussions in the mapped literature range from solar and wind technologies to linking with technologies that enable site-specific nutrient management and laser land leveling (Fig. 2). The first three years of publication mostly discussed technologies related to solar and wind pumps for irrigation. Between 2015 and 2021, the reviewed literature expands to other technologies, such as precision irrigation, mobile-enabled remote irrigation technologies, and technologies that are driven by artificial intelligence (AI) and the Internet of things (IoT).

Drivers of CSI in South Asia

We found three themes that were driving the adoption of CSI in South Asia. The first theme of *climate variability and GHG mitigation* includes research articles citing potential climate impact as the driving force of adoption and implementation. Specific drivers under this theme include climate effects on Pakistan's cotton cultivation (Jamil et al. 2021), the impacts of extreme weather events in Bangladesh like greater frequency and magnitude of cyclones, higher salinity levels, and worsening cold and fog in winter (Jost et al. 2016), and seasonal variation in India (Kishore et al. 2017).

The second theme of *cost savings and support structure* captured articles that herald potential reduction in input costs for farming via CSI adoption and implementation. These costs include—but are not limited to—inputs associated with diesel, electricity, and cost of travel for farmers to secure water for crops (Khalil et al. 2019; Kalita et al. 2021). Articles grouped in this theme also prominently discussed subsidies as a public policy tool for making CSI more affordable to farmers (Djanibekov and Gaur 2018; Shah et al. 2018; Sharma 2021).

The third theme of *water conservation* grouped articles that examined CSI as a strategy for improving water use efficiency. One challenge that emerged in this theme is to foster more efficient use of water without running the risk of over-extraction or over-withdrawal (i.e., Gupta 2019; Sharma et al. 2022). Other studies included in this theme discussed efficient management of irrigation water (Rizwan et al. 2018; Pal et al. 2021) and new approaches to crop cultivation in water scarce contexts (Deelstra et al. 2018). Figure 2 below shows that the frequency of each theme was fairly consistent across each country enrolled in our mapping. Cost savings and support structure were among the most prominent themes, followed by climate considerations. For specifics on the articles included in our driver and barrier themes, we invite readers to consult the tables in the supplementary material for this article (Figs. 3, 4).

Barriers to CSI in South Asia

We found five themes that served as barriers to CSI's adoption in South Asia. The first theme of *financial support*

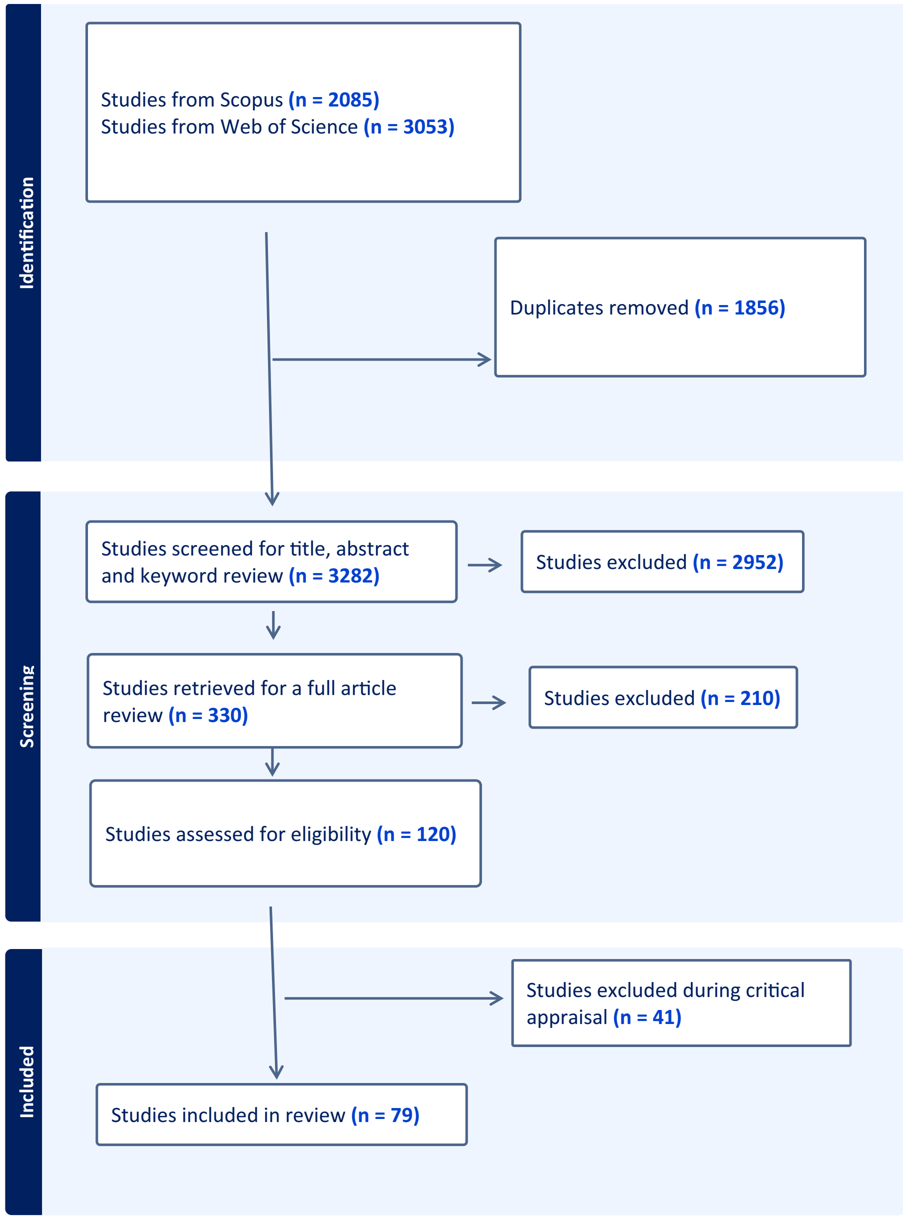

Fig. 1 Identification, selection, and inclusion process for systematic mapping

highlighted the need for more capital availability for farmers to use CSI. The focus of these articles was on government incentives, such as subsidies (Shah et al., 2014, 2018), and stressed how incumbent it is for governments and international NGOs to assist with installation costs (Zhou and Abdullah 2017). Financial support was commonly cited in research articles where public policies, such as agricultural subsidies were not in effect or managed ineffectively (Tankha et al. 2019). In contrast, the second theme of *high initial cost* (while related as a financial prohibition) speaks to the point of adoption at the farmer level. This theme signals that upfront costs provide a barrier even if there is the prospect of savings in the long run. Farmers need sufficient capital at the outset in order to implement CSI.

The third theme of *inadequate practice-based research* shows a lack of sufficient studies to date to inform decisions adequately or illuminate how to pair CSI with other practices or technologies. In the specific case of solar pumps, more research is particularly necessary on how these technologies work best in the field (Kishore et al. 2017). However, with the broader suite of approaches falling under CSI in mind, this theme additionally includes calls for policy-driven science (Jat et al. 2019), more vigorous research at both the farmer and the policy level (Haque et al. 2021), and more systematic investigations of

Table 1 Search queries used in the systematic mapping. The abbreviation “TS” in the Web of Science queries stands for term and fixes the topic field

Sr. no	Scopus query	No. of results	WoS query	No. of results
1	TITLE-ABS-KEY (“South Asia”) AND (TITLE-ABS-KEY (“solar pump”) OR TITLE-ABS-KEY (“solar irrigation”) OR TITLE-ABS-KEY (“solar technology”) OR TITLE-ABS-KEY (“solar technology pumps”) OR TITLE-ABS-KEY (“solar-based pumps”) OR TITLE-ABS-KEY (“precision irrigation”)) AND PUBYEAR > 2010 AND PUBYEAR < 2022	8	TS = (South Asia)AND TS = (solar pump OR solar irrigation OR solar technology OR solar technology pumps OR solar-based pumps OR precision irrigation)	82
2	TITLE-ABS-KEY(“Bangladesh”) OR TITLE-ABS-KEY(“India”) OR TITLE-ABS-KEY(“Nepal”) OR TITLE-ABS-KEY(“Pakistan”) AND TITLE-ABS-KEY(“solar irrigation”) OR TITLE-ABS-KEY(“solar technology”) OR TITLE-ABS-KEY(“solar technology pumps”) OR TITLE-ABS-KEY(“solar-based pumps”) OR TITLE-ABS-KEY(“precision irrigation”) AND PUBYEAR > 2010 AND PUBYEAR < 2022	106	TS = (Bangladesh OR India OR Nepal OR Pakistan)AND TS = (solar pump OR solar irrigation OR solar technology OR solar technology pumps OR solar-based pumps OR precision irrigation)	1445
3	TITLE-ABS-KEY(“Bangladesh”) AND TITLE-ABS-KEY(“India”) AND TITLE-ABS-KEY(“Nepal”) AND TITLE-ABS-KEY(“Pakistan”) AND TITLE-ABS-KEY(“solar irrigation”) OR TITLE-ABS-KEY(“solar technology”) OR TITLE-ABS-KEY(“solar technology pumps”) OR TITLE-ABS-KEY(“solar-based pumps”) OR TITLE-ABS-KEY(“precision irrigation”) AND PUBYEAR > 2010 AND PUBYEAR < 2022	0	TS = (Bangladesh AND India AND Nepal AND Pakistan)AND TS = (solar pump OR solar irrigation OR solar technology OR solar technology pumps OR solar-based pumps OR precision irrigation)	2
4	TITLE-ABS-KEY(“South Asia”) AND TITLE-ABS-KEY(“climate smart” OR “climate-smart” OR “smart”) AND PUBYEAR > 2010 AND PUBYEAR < 2022	68	(TS = (South Asia)) AND TS = (climate smart OR climate-smart OR smart)	136
5	TITLE-ABS-KEY (“climate-smart” AND agric*) AND PUBYEAR > 2010 AND PUBYEAR < 2022	1117	TS = (climate-smart AND agriculture)	849
6	TITLE-ABS-KEY(“solar pump”) OR TITLE-ABS-KEY(“solar irrigation”) OR TITLE-ABS-KEY(“solar technology pumps”) OR TITLE-ABS-KEY(“solar-based pumps”) OR TITLE-ABS-KEY(“precision irrigation”) AND PUBYEAR > 2010 AND PUBYEAR < 2022	786	TS = (“solar pump” OR “solar irrigation” OR “solar technology pumps” OR “solar-based pumps” OR “precision irrigation”)	539

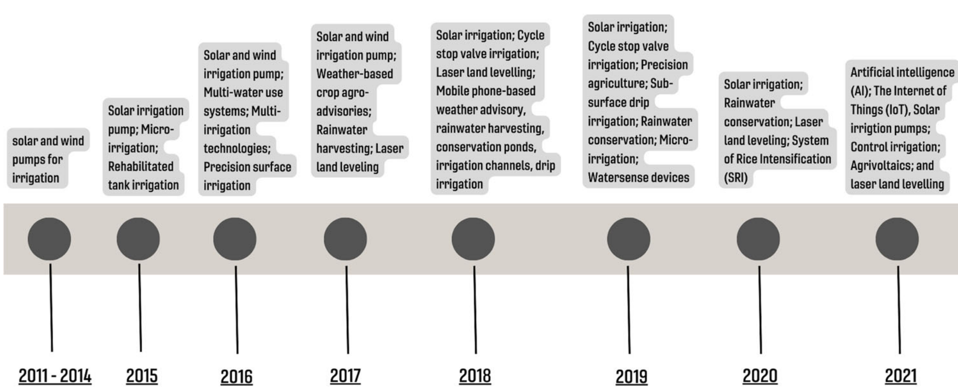

Fig. 2 Temporal trends in CSI technologies in the publications identified and reviewed

CSI that can inform more targeted approaches (Kakraliya et al. 2021). What distinguishes this theme is its identification of standing knowledge gaps in current scholarship.

Our next theme, in turn, focuses on resource gaps at the farmer level. The fourth theme of *lack of access* identifies limited extension services, limited mobility, limited

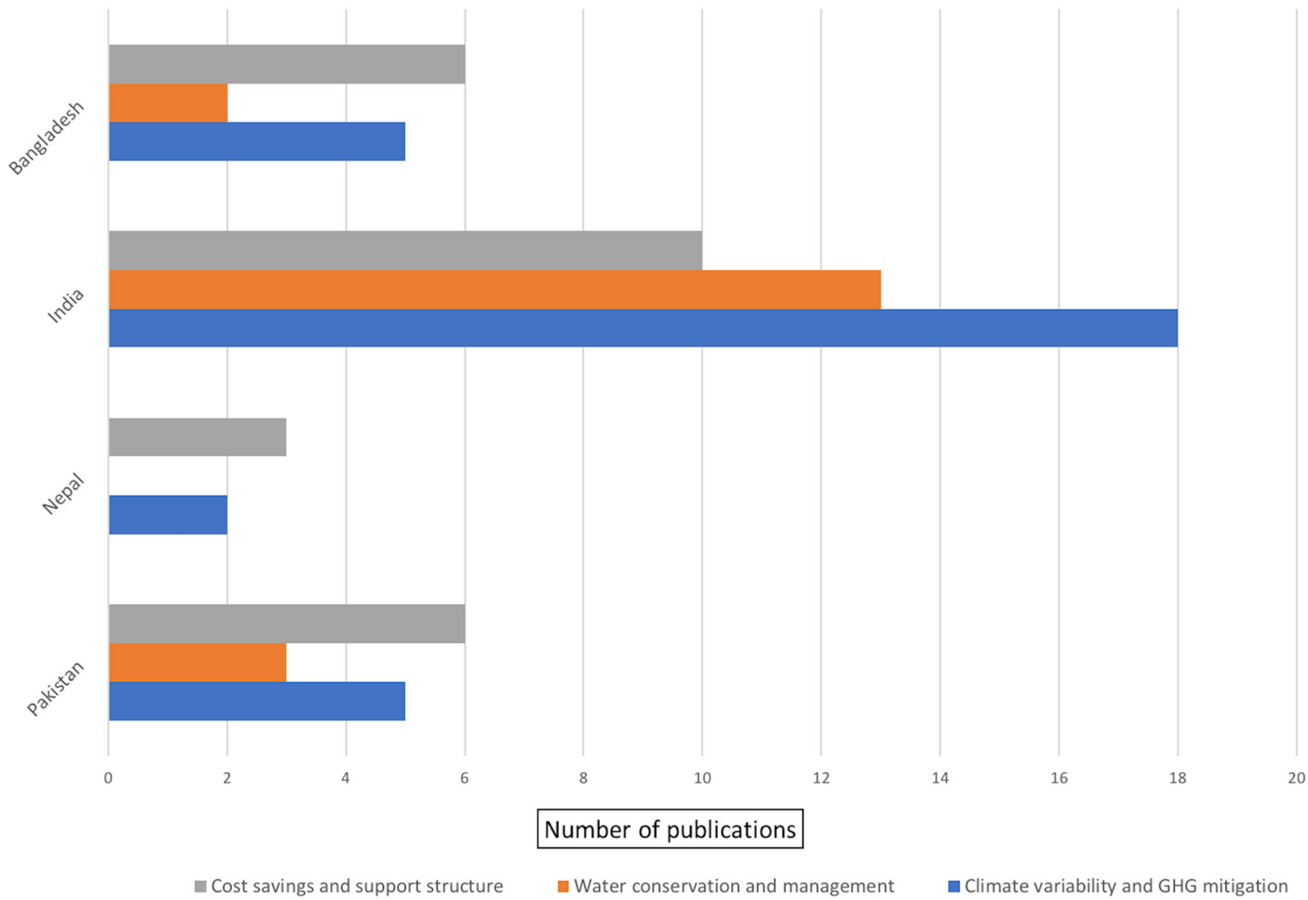

Fig. 3 Categorization of articles by drivers of CSI adoption and country

technology, and limited training as barriers in CSI implementation. There were cases, for instance, where "policies and their implementations are controlled by the non-market players and farmers are reluctant" to adopt (Jamil et al. 2021). There is a need to think more critically about how information is shared and disseminated so as to bolster awareness and understanding about CSI (Mittal and Hariharan 2018). More concrete changes to expand access include improved training facilities (Pal et al. 2021) and installation technicians (Rathore et al. 2018). When farmers are disconnected from the market and extension services, adding an additional cost consideration in terms of transportation was also highlighted as barrier to adoption of CSI (Aryal et al. 2018b). Research signals the need to facilitate extension services and outreach to distant farmers, who may not be well connected to the road and telecommunication infrastructure.

The fifth theme of *structures of power* outlines inequities at the farmer level surrounding caste, class, gender, landholding status, and place-based difference. Seeing potential disruptions in wider CSI adoption as solely technical and not more appropriately as sociotechnical can prove myopic. Whereas the technical perspective sees simple "access to resources" as a panacea for farmers' adoption of CSI (Aryal et al. 2020), the sociotechnical perspective recognizes that access alone does not address distributional challenges brought forward by new technologies. Instead, social inequalities can create risks for those who are already marginalized and underrepresented in the CSI innovation ecosystem. Indeed, access is distinguishable as an "*ability* to derive benefits from things" that thus entails "means, relations, and processes that enable various actors to derive benefits from resources" (Ribot and Peluso 2003). There is a need to develop social infrastructure around CSI accordingly to account for relations and processes that can truly benefit the underserved in South Asia (Dhital et al. 2016).

Country-specific results

In research focused in *Bangladesh*, we found a specific focus in the mapped studies on mechanisms needed to smooth the burden of high initial costs of solar pumps, despite significant future cost savings afforded to farmers (Sarkar and Ghosh 2017; Shoeb and Shafiullah 2018; Rana et al. 2021). CSI implementation efforts succeeded when the focus of technology was on adaptation (Jost et al.

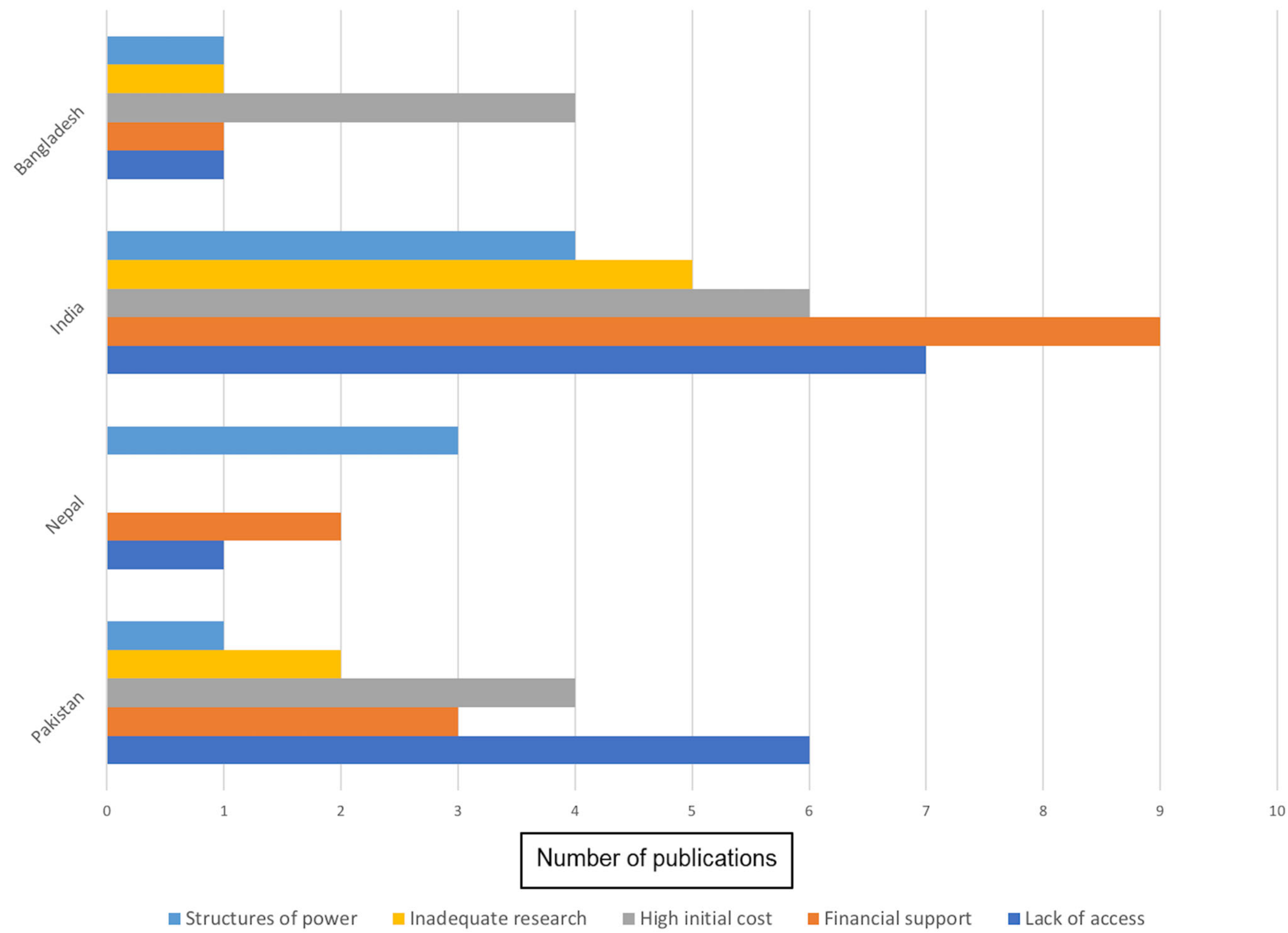

Fig. 4 Categorization of articles by barriers to CSI implementation and country

2016), where it led to collaboration among local technology partners and created new jobs (Kibria et al. 2017), and when government focused on providing financial support for transitioning to sustainable and reliable energy for the people of Bangladesh (Rana et al. 2021). Gaps that inhibit wide adoption of CSI technologies included an absence of national policies on CSI that created challenges for subnational policy implementation (Rana et al. 2021), an absence of resources toward upscaling of CSI (Aggarwal et al. 2018), and overreliance on multinational financial institutions for technology transfer from the Global North to South (Sarkar and Ghosh 2017).

Research papers on *India* exhibited a need for co-production of robust and knowledge-based resources to understand how CSI can aid with achieving India's adaptation and mitigation goals. Articles mapped indicated that public policies and programs for solar irrigation (Shah et al. 2014, 2018; Santra 2021) focused mainly on public–private partnerships that aimed to bolster farmers' access to financial and lending markets (Pal et al. 2021). Discussions of limited access (Alam and Sikka 2019; Dutta et al. 2019), knowledge gaps (Aryal et al. 2018a; Dutta et al. 2019), lack of capital (Djanibekov and Gaur 2018), and policy-driven science focused on a range of energy technologies as part of a growing net-zero carbon commitment were some of the factors influencing CSI's adoption in India (Jat et al. 2019). At the same time, several challenges associated with CSI adoption were highlighted, including the need for well-defined regulation of these technologies for smallholders (Kalita et al. 2021); inclusion of water pricing to manage extraction (Kishore et al. 2017), and more attention to smallholders' inclusion in this technological revolution (Lopez-Ridaura et al. 2018).

While the same need for cost savings also emerged out of studies from *Nepal*, structures of power and lack of capital also remained strong challenges in CSI's implementation efforts. The gender gap affects availability of land and resources between different gender identities (Paudyal et al. 2019; Khatri-Chhetri et al. 2020). The literature on Nepal shows that management of CSI succeeds when there are concerted and coordinated efforts at multiple levels of government (Adhikari 2018) and when it is attuned to needs for female empowerment (Khapung 2016; Paudyal et al. 2019). Obstacles for CSI governance cited in the research mapped were primarily economic, i.e., greater financial incentives for farmers could incentivize them to be more productive and use less water (Adhikari 2018; Paudyal et al. 2019; Foster et al. 2021).

Studies on *Pakistan* indicated that high initial costs were one of the key challenges for uneven adoption of CSI. Without a financial safety net for interested farmers, those with more “education, access to credit, tubewell ownership, farming experience, and access to extension services” are more likely to adopt, excluding those without these resources and capacities (Jamil et al. 2021). Though articles focused on Pakistan did not often discuss matters of management, exceptions included articles that focused on adaptive capacity and capacity building (Khan et al. 2021a, b) as well as campaigns toward awareness and improved access (Imran et al. 2018), especially among smallholders as enabling governance (Jamil et al. 2021). Primary barriers to CSI adoption include inadequate resources (Dhakal et al. 2021) and a “dire need to develop adoption policy to keep in mind the perspective and adoption capacity of the real stakeholders (farmers)“ (Jamil et al. 2021).

Unlike the consistency we found in the drivers across the region, the barriers vary considerably by country. With the exception of Nepal, which has a comparatively limited sample size, structures of power are rather deemphasized when considered alongside the other prominent themes. In the case of Bangladesh, more articles left barriers unaddressed than recognize the need to address inequity.

DISCUSSION

This review highlighted how innovations in CSI technologies have evolved in South Asia. We were able to map CSI technologies and their level of importance for farmers and policy makers in South Asia. Through an exhaustive mapping of the literature, we identified different drivers and barriers to CSI adoption and implementation in South Asia. We found that CSI technologies are primarily driven by climate effects, reducing GHG emissions, and intentions of truncating input costs and water saving. We also examined how the drivers and barriers of CSI varied across the region and between four countries: India, Pakistan, Nepal, and Bangladesh. We found that an adoption of CSI technologies in Bangladesh takes place when these technologies are financially incentivized and collaboration with local partners are facilitated, while in Nepal, CSI adoption largely depends on concerted efforts at multiple levels of governance with an additional focus on gender. CSI adoption in India and Pakistan is influenced by farmers' access to financial and lending markets and extension services. The barriers to CSI adoption varies considerably across South Asian countries, but we were able to map out key barriers that are related to financial facilitations, input costs, access to resources, and existing power relations.

In this section, having noted various limitations in section “Limitations”, we discuss three important implications of our study findings. First, our results reveal the importance of collaborative learning between countries (Bangladesh, India, Nepal, and Pakistan) given commonalities and differences in the drivers to and barriers of CSI adoption in the region. Countries in this region can benefit from learning about what kind of institutions and incentives are shaping CSI innovation, how CSI innovations are facilitating or hindering climate change adaptation, mitigation, and food security, and how effective these policies work for those people who have been historically marginalized and underrepresented in agriculture, e.g., women, children, ethnic minorities, and landless peasants. Climate change disproportionately affects smallholders, especially those who are young or identify as female. This is, often, a ripple effect of exclusion practices—be it who owns land, has access to needed tools and resources, or gets to voice their perspectives in policy development (those who are privileged and in power). If these exclusions continue, one would expect CSI development to continue to fall short in reflecting a full span of stakeholder needs and values. As CSI efforts expand, these deeply rooted contextual dimensions cannot be ignored if one expects CSI not to further exacerbate inequity (Taneja et al. 2019; Closas and Rap. 2017).

Second, from an academic and practical perspective for RI, setting up the means for collaborative learning can help fill in the broader gap in RI scholarship on how to foster inclusion specifically in the Global South. Various participatory movements from co-design (DiSalvo et al. 2011; Berthet et al. 2018; Agid and Chin 2019; Ayre et al. 2019; Baibarac and Petrescu 2019) to living labs (Ballon et al. 2005; Erickson et al. 2005; Niitamo et al. 2006; Almirall and Wareham 2008; Bergvall-Kåreborn and Ståhlbröst 2009; Leminen et al. 2012; Dell'Era and Landoni 2014; Leminen and Westerlund 2019) have found traction as of late in creating means of different parties surrounding agricultural innovation becoming mutually responsive and coordinating across regions. While our findings give credence to experimentation with and through such approaches around CSI in South Asia to embolden work on responsible governance in global contexts, they also warrant exercising caution to ensure they meet needs that are identified by our review in terms of a collective effort toward coordinated research, outreach, and equity efforts rather than solely capital or profit. This rightfully puts the focus on building infrastructure and community as a matter of governance (Zavratnik et al. 2019; Gamache et al. 2020).

Finally, we highlight the importance of reimagining what responsibility means in the context of innovation in South Asia, and how innovation interventions can become more sensitive to discussions of power and marginalization of social groups and individuals in rural agrarian communities. RI scholarship has demonstrated top-down innovation processes yield predictable results: limited social traction and the extension of standing inequities. Previous research on CSA broadly indicates that insufficient coordination in institutional interventions and governance schemes at different levels, along with inattention to gender inequity, are themes in the literature affecting smallholder adoption (Ogunyiola et al. 2022). In Africa as an example, literature has yet to take the opportunity to conceptualize responsibility at the level of states and institutions in favor of focusing on suites of technologies and on-farm adaptation practices, leading to questions of purpose and interests served in adoption (Vercillo et al 2022). In the specific case of CSI movement in South Asia, we accordingly found an overall dearth of critically engaged conversation on inequalities, smallholder operations, and needs for community infrastructure.

Here, we argue that living laboratories (LLs) can be used to test ideas in rural communities in South Asia, prior to imagining how they will scale up. This means, in other words, taking a vertical slice of the innovation ecosystem and conducting deep sociotechnical assessments of CSI with farming communities in South Asia in an iterative and interactive manner. We contend that a LL approach adds much to the conversation as a means of enacting trust among farmers. LLs place users front and center, taking advantage of communication technologies to test innovations in development across sites in everyday environments of use. Research is beginning to conceptualize trust in rural interventions (Zavratnik et al. 2019), farming (Guzman et al. 2008), open innovation (Puerari et al. 2018), and co-production methodologies (Nesti 2017). Rural Living Labs (RLLs) specifically capitalize on the benefits of rural citizens' and farmers' input into design while providing underserved communities with technology and networking opportunities. Zavratnik et al. (2019) and Gamache et al. (2020) assert such labs should start with assessing and building community first as a matter of equity and focus on sustainability transitions rather than solely focusing on building a successful or profitable prototype. This may include constructing new services, reskilling programs, and governance structures. Specifically, LLs, in conjunction with regional governments, can assist in transitions as farmers seek innovative solutions for agricultural, food, environmental, and social concerns through the facilitation of new organizational models that organize the provision of goods and services (García-Llorente et al. 2019).

In our exploration of the implementation of new technologies in Global South, we are attuned to several cultural and geographical blindspots of RI. Specifically, the conceptualization of RI from a Global South perspective has been weak, leading to assumptions of Western conceptions of democracy and justice that is used as a lens to evaluate science and scientific expertise (Prasad 2020). By referring to these Western conceptions, we mean to acknowledge the predominance of RI work coming out of Western Europe specifically as a by-product of funding requirements from the European Union. Research from Global South by contrast has highlighted the importance of paying attention to context and culturally specific construction of RI, whereby researchers can avoid the trap of assuming social and political conditions for innovation to be similar to the Global North (Sharma 2021; Prasad 2020).

CONCLUSION

Our article has mapped the evolution of CSI in four South Asian countries (Bangladesh, India, Nepal, and Pakistan) and deployed an RI framework to map drivers and barriers to better understand the status of CSI in each country. We identified the following drivers of CSI adoption in South Asia: *climate variability and greenhouse gas mitigation, cost savings and support structure, water conservation and management.* Regarding barriers to adoption of CSI technologies, our study identified five themes that include *financial support, high initial cost, inadequate practice-based research, lack of knowledge and/or access* and *structures of power.* Our study also revealed many country-specific results. In Bangladesh, CSI adoption increased when linked with climate adaptation and when the government provided financial support. Governance challenges in Bangladesh included absence of federal policy on CSI, absence of financial resources to enable adoption, and a dependency on technology transfers from the global North. In India, linking CSI with the nation's broader climate and sustainability targets improved adoption, as well as public–private partnerships. Governance challenges for CSI included insufficient and ambiguous regulation, exclusion of smallholders in CSI procedures and implementation, and lack of consistent and effective water pricing to curb over-extraction and wastage. In Nepal, CSI adoption improved when governance institutions collaborate across scales toward implementation and when projects are designed to facilitate female empowerment. Challenges to CSI governance in Nepal include the dearth of financial resources that limits incentives and subsidies for adoption. In Pakistan, opportunities for CSI adoption lie in framing the technologies as enhancing adaptive capacity to climate change and ensuring increased and equal access to water resources for farmers. Challenges to CSI adoption include high initial costs and inadequate financial resources.

The consistency of the most impactful drivers cited in research on each country and the variability of the most pressing barriers from country to country signals that knowledge-sharing across contexts reasonable stands as the next step to lessen the impact of barriers, meriting a collaborative infrastructure for knowledge exchange. What we also see from the standing literature confirms the possibility that existing efforts may only continue to privilege large scale agriculture and wealthy farmers and leave smallholders behind. In addition, the fact that most of the literature we found does not at least present, let alone forge dialogue with, considerations of power and difference highlights the opportunity and high stakes for critical research in CSI planning and practices. While the co-productive opportunities we present are as susceptible to similar critiques of Western provenance as RI, we endorse co-design and LL frameworks as a step in the right direction in realizing the kind of governance that RI desires that has found proven application in non-Western agricultural contexts. We therefore conclude that an opportunity exists for scholars to experiment with more participatory means to enact principles of responsible governance in ways that meet the needs of interested farmers.

Acknowledgements This research was supported by a +Policy Research Fellowship from the Institute for Society, Culture and Environment at Virginia Tech and based upon work supported by the National Science Foundation under Grant Number 2202706 and 2026431. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

REFERENCES

Adhikari, S. 2018. Drought impact and adaptation strategies in the mid-hill farming system of western Nepal. *Environments* 5: 101.

Agarwal, R., V. Balasundharam, P. Blagrave, E. Cerutti, R. Gudmundsson, and R. Mousa. 2021. Climate change in South Asia: Further need for mitigation and adaptation. *International Monetary Fund*. https://www.imf.org/-/media/Files/Publications/WP/2021/English/wpiea2021217-print-pdf.ashx.

Aggarwal, P.K. 2015. Climate-smart agriculture in South Asia: Opportunities and constraints in scaling out [Abstract only] In Centre de cooperation Internationale en Recherche Agronomique pour le Developpement (CIRAD). 3rd Global Science Conference on Climate-Smart Agriculture, Montpellier, France, 16–18 March 2015. Parallel session L1 regional dimensions, 36–37. Paris, France: Centre de cooperation Internationale en Recherche Agronomique pour le Developpement (CIRAD).

Aggarwal, P.K., A. Jarvis, B.M. Campbell, R.B. Zougmoré, A. Khatri-Chhetri, S.J. Vermeulen, A.M. Loboguerrero, L.S. Sebastian, et al. 2018. The climate-smart village approach: Framework of an integrative strategy for scaling up adaptation options in agriculture.

Agid, S., and E. Chin. 2019. Making and negotiating value: Design and collaboration with community led groups. *CoDesign* 15: 75–89.

Ahmed, M., and S. Suphachalasai. 2014. *Assessing the costs of climate change and adaptation in South Asia*. Asian Development Bank. http://hdl.handle.net/11540/46.License:CCBY3.0IGO.

Alam, M.F., and A.K. Sikka. 2019. Prioritizing land and water interventions for climate-smart villages. *Irrigation and Drainage* 68: 714–728.

Almirall, E., and J. Wareham. 2008. Living labs and open innovation: Roles and applicability. *eJOV: The Electronic Journal for Virtual Organization & Networks, 10*.

Aryal, J.P., C.R. Farnworth, R. Khurana, S. Ray, T.B. Sapkota, and D.B. Rahut. 2020. Does women's participation in agricultural technology adoption decisions affect the adoption of climate-smart agriculture? Insights from Indo-Gangetic Plains of India. *Review of Development Economics* 24: 973–990.

Aryal, J.P., M.L. Jat, T.B. Sapkota, A. Khatri-Chhetri, M. Kassie, and S. Maharjan. 2018a. Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. *International Journal of Climate Change Strategies and Management*.

Aryal, J.P., D.B. Rahut, S. Maharjan, and O. Erenstein. 2018b. Factors affecting the adoption of multiple climate-smart agricultural practices in the Indo-Gangetic Plains of India. In *Natural resources forum*, 42, 141–158. Oxford, UK: Blackwell Publishing Ltd.

Ayre, M., V.M. Collum, W. Waters, P. Samson, A. Curro, R. Nettle, J.-A. Paschen, B. King, and N. Reichelt. 2019. Supporting and practising digital innovation with advisers in smart farming. *NJAS: Wageningen Journal of Life Sciences* 90–91: 100302.

Baibarac, C., and D. Petrescu. 2019. Co-design and urban resilience: Visioning tools for commoning resilience practices. *CoDesign* 15: 91–109.

Ballon, P., J. Pierson, and S. Delaere. 2005. Test and experimentation platforms for broadband innovation: Examining European practice.

Barker, R., and F. Molle. 2004. *Evolution of irrigation in South and Southeast Asia.* Colombo, Sri Lanka: Comprehensive Assessment Secretariat. (Comprehensive Assessment Research Report 5).

Barrett, H., and D.C. Rose. 2020. Perceptions of the fourth agricultural revolution: What's in, what's out, and what consequences are anticipated? *Sociologia Ruralis*.

Bergvall-Kåreborn, B., and A. Ståhlbröst. 2009. Living lab: An open and citizen-centric approach for innovation. *International Journal of Innovation and Regional Development* 1: 356–370.

Berthet, E.T., G.M. Hickey, and L. Klerkx. 2018. Opening design and innovation processes in agriculture: Insights from design and management sciences and future directions. *Agricultural Systems* 165: 111–115.

Bingham, A.J., and P. Witkowsky. 2022. Deductive and inductive approaches to qualitative data. In *Analyzing and interpreting qualitative data: After the interview*, ed. C. Vanover, P. Mihas, and J. Saldaña, 133–146. London: SAGE Publications.

Bogner, A., and H. Torgersen. 2018. Precaution, responsible innovation and beyond—In search of a sustainable agricultural biotechnology policy. *Frontiers in Plant Science*.

Closas, A., and E. Rap. 2017. Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy* 104: 33–37.

Deelstra, J., U.S. Nagothu, K.R. Kakumanu, Y.R. Kaluvai, and S.R. Kallam. 2018. Enhancing water productivity using alternative rice growing practices: A case study from Southern India. *The Journal of Agricultural Science* 156: 673–679.

Dell'Era, C., and P. Landoni. 2014. Living Lab: A methodology between user-centered design and participatory design. *Creativity and Innovation Management* 23: 137–154.

Dhakal, M.P., A. Ali, M.Z. Khan, N. Wagle, G.M. Shah, M.M. Maqsood, and A. Ali. 2021. Agricultural water management challenges in the Hunza River Basin: Is a solar water pump an alternative option? *Irrigation and Drainage* 70: 644–658.

Dhital, R.P., Y. Ito, S. Kaneko, S. Komatsu, R. Mihara, and Y. Yoshida. 2016. Does institutional failure undermine the physical design performance of solar water pumping systems in rural Nepal? *Sustainability* 8: 770.

DiSalvo, C., T. Lodato, L. Fries, B. Schechter, and T. Barnwell. 2011. The collective articulation of issues as design practice. *CoDesign* 7: 185–197.

Djanibekov, U., and V. Gaur. 2018. Nexus of energy use, agricultural production, employment and incomes among rural households in Uttar Pradesh, India. *Energy Policy* 113: 439–453.

Dutta, V., M. Vimal, S. Singh, and R.P. Singh. 2019. Agricultural practices in a drought-prone region of India: Opportunities for S&T innovations. *World Journal of Science, Technology and Sustainable Development*.

Eriksson, M., V.P. Niitamo, and S. Kulkki. 2005. State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation-a European approach. Lulea: Center for Distance- spanning Technology. Lulea University of Technology Sweden: Lulea.

Fisher, E., and A. Rip. 2013. Responsible innovation: Multi-level dynamics and soft intervention practices. In *Responsible innovation: Managing the responsible emergence of science and innovation in society*, ed. R. Owen, J. Bessant, and M. Heintz, 165–183. Wiley.

Foster, T., R. Adhikari, S. Adhikari, S. Justice, B. Tiwari, A. Urfels, and T.J. Krupnik. 2021. Improving pumpset selection to support intensification of groundwater irrigation in the Eastern Indo-Gangetic Plains. *Agricultural Water Management* 256: 107070.

Foster, S., A. Lawrence, and B. Morris. 1998. *Groundwater in urban development: Assessing management need and formulating policy strategies.* World Bank technical paper no. 390. Washington, D.C.: The World Bank.

Frankelius, P., C. Norrman, and K. Johansen. 2019. Agricultural innovation and the role of institutions: Lessons from the game of drones [Article]. *Journal of Agricultural and Environmental Ethics* 32: 681–707.

Gamache, G., J. Anglade, R. Feche, F. Barataud, C. Mignolet, and X. Coquil. 2020. Can living labs offer a pathway to support local agri-food sustainability transitions? *Environmental Innovation and Societal Transitions* 37: 93–107.

García-Llorente, M., I. Pérez-Ramírez, C. Sabán de la Portilla, C. Haro, and A. Benito. 2019. Agroecological strategies for reactivating the agrarian sector: The case of Agrolab in Madrid. *Sustainability* 11: 1181.

Gardezi, M., D.T. Adereti, R. Stock, and A. Ogunyiola. 2022. In pursuit of responsible innovation for precision agriculture technologies. *Journal of Responsible Innovation*, 1–24.

Goap, A., D. Sharma, A.K. Shukla, and C.R. Krishna. 2018. An IoT based smart irrigation management system using Machine learning and open source technologies. *Computers and Electronics in Agriculture* 155: 41–49.

Gupta, E. 2019. The impact of solar water pumps on energy-water-food nexus: Evidence from Rajasthan, India. *Energy Policy* 129: 598–609.

Guzman, J.G., H. Schaffers, V. Bilicki, C. Merz, and M. Valenzuela. 2008, June. Living labs fostering open innovation and rural development: Methodology and results. *2008 IEEE International Technology Management Conference (ICE)*, 1–8. IEEE.

Haddaway, N.R., and B. Macura. 2018. The role of reporting standards in producing robust literature reviews. *Nature Climate Change*.

Haque, A., N. Islam, N.H. Samrat, S. Dey, and B. Ray. 2021. Smart farming through responsible leadership in Bangladesh: Possibilities, opportunities, and beyond. *Sustainability* 13: 4511.

Imran, M.A., A. Ali, M. Ashfaq, S. Hassan, R. Culas, and C. Ma. 2018. Impact of Climate Smart Agriculture (CSA) practices on cotton production and livelihood of farmers in Punjab, Pakistan. *Sustainability* 10: 2101.

IPCC. 2021. Summary for policymakers. In *Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change*, eds. V. Masson-Delmotte, P. Zhai, and A. Pirani, et al., 1–41. Cambridge: Cambridge University Press.

Jamil, I., W. Jun, B. Mughal, M.H. Raza, M.A. Imran, and A. Waheed. 2021. Does the adaptation of climate-smart agricultural practices increase farmers' resilience to climate change? *Environmental Science and Pollution Research* 28: 27238–27249.

Jat, H.S., P.C. Sharma, A. Datta, M. Choudhary, S.K. Kakraliya, H.S. Sidhu, B. Gerard, M.L. Jat, et al. 2019. Re-designing irrigated intensive cereal systems through bundling precision agronomic innovations for transitioning towards agricultural sustainability in North-West India. *Scientific Reports* 9: 1–14.

Jost, C., F. Kyazze, J. Naab, S. Neelormi, J. Kinyangi, R. Zougmore, P. Aggarwal, G. Bhatta, et al. 2016. Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development* 8: 133–144.

Kakraliya, S.K., H.S. Jat, T.B. Sapkota, I. Singh, M. Kakraliya, M.K. Gora, P.C. Sharma, M.L. Jat. 2021. Effect of climate-smart agriculture practices on climate change adaptation, greenhouse gas mitigation and economic efficiency of rice-wheat system in India. *Agriculture* 11: 1269.

Kalita, U., A.K. Hazarika, A. Phukan, D. Kakati, and M. Das. 2021. Breaking the mould: Understanding the practicality of solar water pumps among small tea planters in a South Asian State of India. *Energy, Ecology and Environment* 6: 292–306.

Khalil, A., A. Javed, and H. Bashir. 2019. Evaluation of carbon emission reduction via GCIP projects: Creating a better future for Pakistan. *Earth Systems and Environment* 3: 19–28.

Khan, M.S., A. Tahir, I. Alam, S. Razzaq, M. Usman, W.U.K. Tareen, N.A. Baig, S. Atif, et al. 2021a. Assessment of solar photovoltaic water pumping of WASA tube wells for irrigation in Quetta Valley Aquifer. *Energies* 14: 6676.

Khan, N.A., Q. Gao, M. Abid, and A.A. Shah. 2021b. Mapping farmers' vulnerability to climate change and its induced hazards: Evidence from the rice-growing zones of Punjab, Pakistan. *Environmental Science and Pollution Research* 28: 4229–4244.

Khapung, S. 2016. Transnational feminism and women's activism: Building resilience to climate change impact through women's empowerment in climate smart agriculture. *Asian Journal of Women's Studies* 22: 497–506.

Khatri-Chhetri, A., and P.K. Aggarwal. 2017. Adapting agriculture to changing climate in South Asia. *World Agriculture*.

Khatri-Chhetri, A., P.P. Regmi, N. Chanana, and P.K. Aggarwal. 2020. Potential of climate-smart agriculture in reducing women farmers' drudgery in high climatic risk areas. *Climatic Change* 158: 29–42.

Kibria, G., A.K. Haroon, and D. Nugegoda. 2017. An innovative model for engagement of rural citizens/community of Bangladesh with climate Change. *Journal of Climate Change* 3: 73–80.
Kishore, A., P.K. Joshi, and D. Pandey. 2017. Harnessing the sun for an evergreen revolution: A study of solar-powered irrigation in Bihar. *India. Water International* 42: 291–307.
Klerkx, L., and D. Rose. 2020. Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? [Article]. *Global Food Security* 24: 100347.
L'Astorina, A., I. Tomasoni, A. Basoni, and P. Carrara. 2015. Beyond the dissemination of Earth Observation research: Stakeholders' and users' involvement in project co-design. *JCOM* 14: C03.
Leminen, S., and M. Westerlund. 2019. Living labs: From scattered initiatives to a global movement. *Creativity and Innovation Management* 28: 250–264.
Leminen, S., M. Westerlund, and A.G. Nyström. 2012. Living labs as open-innovation networks. *Technology Innovation Management Review* 2: 6–11.
Lopez-Ridaura, S., R. Frelat, M.T. van Wijk, D. Valbuena, T.J. Krupnik, and M.L. Jat. 2018. Climate smart agriculture, farm household typologies and food security: An ex-ante assessment from Eastern India. *Agricultural Systems* 159: 57–68.
Mamidipudi, A., and N. Frahm. 2020. Turning straw to gold: Mobilising symmetry in responsible research and innovation [Article]. *Science, Technology and Society* 25: 223–239.
Mittal, S., and V.K. Hariharan. 2018. Mobile-based climate services impact on farmers risk management ability in India. *Climate Risk Management* 22: 42–51.
Molle, F. (2003). *Development trajectories of river basins: A conceptual framework.* Research Paper No 72. Colombo: International Water Management Institute.
Nesti, G. 2017. Co-production for innovation: The urban living lab experience. *Policy and Society* 37: 310–325.
Niitamo, V.P., S. Kulkki, M. Eriksson, and K.A. Hribernik. 2006, June. State-of-the-art and good practice in the field of living labs. In *2006 IEEE international technology management conference (ICE)*, 1–8. IEEE.
Ogunyiola, A., M. Gardezi, and S. Vij. 2022. *Smallholder farmers' engagement with climate smart agriculture in Africa: Role of local knowledge and upscaling*. Climate Policy.
Pal, B.D., S. Kapoor, S. Saroj, M.L. Jat, Y. Kumar, and K.H. Anantha. 2021. Adoption of climate-smart agriculture technology in drought-prone area of India–implications on farmers' livelihoods. *Journal of Agribusiness in Developing and Emerging Economies*.
Pakistan Suffers Record Flooding, Turning Villages Into Islands—The New York Times. https://www.nytimes.com/2022/09/14/world/asia/pakistan-floods.html. Accessed 13 Nov 2022.
Pant, L.P. 2019. Responsible innovation through conscious contestation at the interface of agricultural science, policy, and civil society. *Agriculture and Human Values* 36: 183–197.
Paudyal, B.R., N. Chanana, A. Khatri-Chhetri, L. Sherpa, I. Kadariya, and P. Aggarwal. 2019. Gender integration in climate change and agricultural policies: The case of Nepal. *Frontiers in Sustainable Food Systems* 3: 66.
Puerari, E., J.I. De Koning, T. Von Wirth, P.M. Karré, I.J. Mulder, and D.A. Loorbach. 2018. Co-creation dynamics in urban living labs. *Sustainability* 10: 1893.
Prasad, C. 2020. Constructing alternative socio-technical worlds: Re-imagining RRI through SRI in India. *Science, Technology and Society* 25: 291–307.
Rana, J., M. Kamruzzaman, M.H. Oliver, and K. Akhi. 2021. Financial and factors demand analysis of solar powered irrigation system in Boro rice production: A case study in Meherpur district of Bangladesh. *Renewable Energy* 167: 433–439.
Rathore, P.K.S., S.S. Das, and D.S. Chauhan. 2018. Perspectives of solar photovoltaic water pumping for irrigation in India. *Energy Strategy Reviews* 22: 385–395.
Ribot, J., and N.L. Peluso. 2003. A theory of access. *Rural Sociology* 68: 153–181.
Rizwan, M., A. Bakhsh, X. Li, L. Anjum, K. Jamal, and S. Hamid. 2018. Evaluation of the impact of water management technologies on water savings in the lower chenab canal command area, Indus River Basin. *Water* 10: 681.
ROSES. 2017. https://www.roses-reporting.com/.
Santra, P. 2021. Performance evaluation of solar PV pumping system for providing irrigation through micro-irrigation techniques using surface water resources in hot arid region of India. *Agricultural Water Management* 245: 106554.
Sarkar, M.N.I., and H.R. Ghosh. 2017. Techno-economic analysis and challenges of solar powered pumps dissemination in Bangladesh. *Sustainable Energy Technologies and Assessments* 20: 33–46.
Shah, T., A. Rajan, G.P. Rai, S. Verma, and N. Durga. 2018. Solar pumps and South Asia's energy-groundwater nexus: Exploring implications and reimagining its future. *Environmental Research Letters* 13: 115003.
Shah, T., S. Verma, and N. Durga. 2014. Karnataka's smart, new solar pump policy for irrigation. *Economic and Political Weekly* 49: 10–14.
Sharma, A. 2021, May. Environmental governance in rural India: diffusion of solar powered irrigation technologies. In *Forum for development studies*, 48, 225–245. Routledge.
Sharma, G., A. Singh, and S. Jain. 2022. A hybrid deep neural network approach to estimate reference evapotranspiration using limited climate data. *Neural Computing and Applications* 34: 4013–4032.
Shoeb, M.A., and G.M. Shafiullah. 2018. Renewable energy integrated islanded microgrid for sustainable irrigation—A Bangladesh perspective. *Energies* 11: 1283.
Shilomboleni, H. 2020. Political economy challenges for climate smart agriculture in Africa. *Agriculture and Human Values* 37: 1195–1206. https://doi.org/10.1007/s10460-020-10126-5.
Simelton, E., and M. McCampbell. 2021. Do digital climate services for farmers encourage resilient farming practices? Pinpointing gaps through the responsible research and innovation framework [Article]. *Agriculture (Switzerland)* 11: 953.
Stilgoe, J., R. Owen, and P. Macnaghten. 2013. Developing a framework for responsible innovation. *Research Policy* 42: 1568–1580.
Taneja, G., B.D. Pal, P.K. Joshi, P.K. Aggarwal, and N.K. Tyagi. 2019. Farmers' preferences for climate-smart agriculture—An assessment in the Indo-Gangetic Plain. In Climate smart agriculture in South Asia, 91–111. Singapore: Springer.
Tankha, S., D. Fernandes, and N.C. Narayanan. 2019. Overcoming barriers to climate smart agriculture in India. *International Journal of Climate Change Strategies and Management*.
Thapa, R.K., T. Iakovleva, and L. Foss. 2019. Responsible research and innovation: A systematic review of the literature and its applications to regional studies. *European Planning Studies* 27: 2470–2490.
Tricarico, L., A. Galimberti, A. Campanaro, C. Magoni, and M. Labra. 2020. Experimenting with RRI tools to drive sustainable

agri-food research: The SASS case study from Sub-Saharan Africa [Article]. *Sustainability (Switzerland)* 12: 827.

Tucker, J.B., and R.A. Zilinskas. 2006. The promise and perils of synthetic biology. *New Atlantis* 12: 25–45.

USDA. 2011. Definitions: Sustainability and Food Systems. Accessed March 29, 2023. Retrieved from https://www.usda.gov/oce/sustainability/definitions.

Vij, S., R. Biesbroek, R. Stock, M. Gardezi, A. Ishtiaque, A. Groot, and K. Termeer. 2021. 'Power-Sensitive Design Principles' for climate change adaptation policy-making in South Asia. *Earth System Governance* 9: 100109.

Vercillo, S., C. Huggins, and L. Cochrane. 2022. How is gender investigated in African climate change research? A systematic review of the literature. *Ambio* 51: 1045–1062. https://doi.org/10.1007/s13280-021-01631-w.

Von Schomberg, R. 2013. A vision of responsible innovation. In *Responsible innovation*, ed. R. Owen, M. Heintz, and J. Bessant. London: John Wiley.

Wong, S. 2019. Decentralised, off-grid solar pump irrigation systems in developing countries—Are they pro-poor, pro-environment and pro-women? In *Climate change-resilient agriculture and agroforestry*, 367–382. Cham: Springer.

Zavratnik, V., A. Superina, and E. Stojmenova Duh. 2019. Living labs for rural areas: Contextualization of living lab frameworks, concepts and practices. *Sustainability* 11: 3797.

Zhou, D., and Abdullah. 2017. The acceptance of solar water pump technology among rural farmers of northern Pakistan: A structural equation model. *Cogent Food & Agriculture* 3: 1280882.

AUTHOR BIOGRAPHIES

Edward Prutzer is a Postdoctoral Associate at Virginia Tech. His research interests include media studies, online communities, open source collaboration, responsible innovation and sustainability, and Science and Technology Studies (STS).
Address: Department of Sociology, Virginia Tech, 519 McBryde Hall, 225 Stanger Street, Blacksburg, VA 24061, USA.
e-mail: prutzer@vt.edu

Anne Patrick is a PhD student at Virginia Tech. Her research interests include digital sociology, food studies/consumption, political sociology, and inequality.
Address: Department of Sociology, Virginia Tech, 225 Stanger Street, Blacksburg, VA 24061, USA.
e-mail: annemp@vt.edu

Asif Ishtiaque is an Assistant Professor at Missouri State University. His research interests include climate change adaptation, vulnerability, and resilience; climate change and agriculture; sustainable development; land use and land cover change; environmental justice; and environmental governance.
Address: Department of Geography, Geology and Planning, Missouri State University, 901 S. National Ave, Springfield, MO 65897, USA.
e-mail: AsifIshtiaque@MissouriState.edu

Sumit Vij is an Assistant Professor at Sociology & Development Change Group, Wageningen University. His research interests are in questions of power and politics in transboundary waters, climate and disaster governance, urban infrastructure, and peri-urban development.
Address: Sociology & Development Change Group, Wageningen University & Research, Wageningen, Netherlands.
e-mail: sumit.vij@wur.nl

Ryan Stock is an Assistant Professor at Northern Michigan University. His research interests include political ecology, environmental justice, feminist geography, intersectionality, renewable energy, climate change, sustainable development, international development, social justice, and social theory.
Address: Department of Earth, Environmental and Geographical Sciences, Northern Michigan University, 3115 Weston Hall, Marquette, MI 49855, USA.
e-mail: rystock@nmu.edu

Maaz Gardezi (✉) is an Assistant Professor at Virginia Tech. His research interests include social implications of emerging agricultural technologies, climate change and sustainability, responsible innovation and governance, computational social sciences, and participatory design of emerging technologies.
Address: Department of Sociology, Virginia Tech, 518 McBryde Hall, 225 Stanger Street, Blacksburg, VA 24061, USA.
e-mail: maaz@vt.edu