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Coping with Climate Change: A Mixed-Methods Approach to Understanding Irrigation Technology Outcomes in Gujarat, India

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Abstract

Previous research on climate change interventions highlights that adaptation and mitigation strategies must be tailored to local contexts to effectively benefit both people and the environment. However, there remains a gap in analyzing the effectiveness of locally specific climate-related technologies in enhancing food security, improving livelihoods, and addressing social dimensions such as women's autonomy. The authors address that gap by drawing on two data sources, one quantitative and one qualitative, to evaluate the impact of an irrigation technology. Specifically, the authors assess its effectiveness in improving crop yields and addressing issues related to migration, women's autonomy, and economic conditions. The quantitative data come from a 2024 survey of 199 farmers across the Harij, Sami, and Sankheswar blocks of Patan district in Gujarat, India. The qualitative data are based on in-depth interviews conducted in 2019 with 48 farmers from the villages of Nani Chandoori and Dudhkha (Sami block) and Aritha (Harij block).

Keywords

irrigation, water scarcity, climate change, Gujarat, women's autonomy, situated sustainability

Climate change impacts and women's autonomy are deeply interconnected (Husaini and Davies 2022; Ranjitkar 2020). Research indicates that extreme weather events commonly linked to climate change exacerbate resource shortages and contribute to community instability (Easterling et al. 2000; Homer-Dixon, Boutwell, and Rathjens 2011; Sawada and Takasaki 2017; Trenberth, Fasullo, and Shepherd 2015; Ummenhofer and Meehl 2017; Yiadom et al. 2023). One consequence of such instability is a rise in harassment and sexual violence against women, particularly as they travel further from home to seek work (Ahmed 2020) or collect essential resources such as water and firewood (Ahmed, Haq, and Bartiaux 2019). As climate-related pressures intensify, women's health and well-being are increasingly compromised because of persistent exposure to waterborne diseases, heat stress (Serdeczny et al. 2017), and other climate-induced health risks (Ebi and Bowen 2016).

In the absence of community stability, extreme weather events can intensify social conflicts and heighten food insecurity (Deb and Haque 2017; Delina and Cagoco-Guiam 2018; Kihila 2018; Tashmin et al. 2018). These impacts are not experienced equally; rather, they disproportionately affect individuals on the basis of gender and other preexisting vulnerabilities (Afriyie, Ganle, and Adomako 2016; Ajibade, McBean, and Bezner-Kerr 2013; Carter 2021).

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For instance, droughts degrade soil structure, reducing its ability to retain water and stripping it of essential nutrients, thereby making agriculture increasingly unsustainable (Hoa and Vinh 2018). As a result, farmers and agricultural workers face compounding challenges, particularly as food insecurity worsens under these conditions (Elum, Modise, and Marr 2017). Globally, an estimated 40 percent of land is now degraded, and drought accounts for more than 15 percent of disaster-related damages and losses worldwide (UNCCD and FAO 2024).

Although women constitute about half of the world's population and agriculture workforce, producing 60 percent to 80 percent of the food grown in developing countries, only one in five landowners is female (UNCCD and FAO 2024). With fewer than 20 percent of landholders being women, their access to resources in the form of loans and credit is absent, which can limit opportunities and the power of women to make their own decisions. Additionally, women represent only 12 percent of the 881 elected officials in environment-related ministries worldwide, even though research shows that women who are landowners and politicians prioritize land health preservation (Bwalya, Mutandwa, and Chiluba 2023; Turay and Omirin 2023).

In rural areas, climate change poses especially severe challenges for agricultural production, disproportionately affecting women who often have limited access to resources (Barbier and Hochard 2018; Berry et al. 2008; Huq et al. 2015). In Gujarat, India, for instance, unpredictable monsoon seasons undermine opportunities for sustainable livelihoods. Yet women's access to land remains highly restricted: a woman can claim land rights only if she is the sole child and has outlived the oldest male relative, a circumstance that applies to just 2 percent of women (Jain et al. 2023). Although reforms such as the Hindu Succession (Amendment) Act of 2005, which grants daughters equal inheritance rights, and the Forest Rights Act of 2006, which recognizes women's rights to forests, have created a legal framework for greater equity, their implementation has lagged in practice (Jain et al. 2023; Rai 2023). Social norms continue to privilege men's land ownership, and government land distribution projects typically designate the head of household—by default, a man—as the landholder (Jain et al. 2023). As a result, rural women often lack control over household resources and decision-making authority. Ironically, when men migrate in search of work because of declining farm productivity, women assume the burden of sustaining families, which includes collecting fuelwood and water (Ravera et al. 2016; Venkatasubramanian and Ramnarain 2018).

Although women's secure land rights are vital for gender equality, well-being, and climate resilience (Namubiru-Mwaura 2014; Sait 2021), social, political, and economic barriers continue to restrict their ability to manage resources and respond to environmental shocks (Slavchevska et al. 2025). In the absence of structural change, communities have developed localized strategies to mitigate gender disparities and improve livelihoods under environmental stress. Research underscores that interventions must be tailored to local contexts to be effective (Deb and Haque 2017; Khan, Adrika, and Firoz 2004; Kihila 2018; Mah et al. 2020; Shuaibu, Akpoko, and Umar 2014; Tashmin et al. 2018). Yet external policy-driven responses to climate disasters often risk being reactive, poorly adapted, or even undermine community resilience (Dube and Sekhwela 2007; Hulme 2004; Mirza 2003). Communities themselves frequently emphasize the value of local and indigenous practices in coping with climate variability (Opare 2018), though such traditional ecological knowledge is often undervalued by outsiders (Shackeroff and Campbell 2007). Bridging modern scientific knowledge with traditional ecological knowledge can offer complementary rather than competing approaches to adaptation (Oguamanam 2006).

Technological solutions to climate change are, understandably, met with skepticism, given that technological advances during the industrial revolution and the rise of capitalism accelerated ecological degradation, including the greenhouse gas emissions that drive today's climate crisis (Clark, Foster, and Auerbach 2023; Foster, Clark, and Holleman 2021; Stuart, Gunderson, and Petersen 2020). Moreover, relying on technology as a substitute for women's land rights risks entrenching the very inequalities that exacerbate vulnerability, while stalling efforts to close the gender gap in land distribution (Klein 2014; Stuart et al. 2020). Nonetheless, when technologies are locally developed and context specific, they can provide meaningful benefits by addressing environmental challenges alongside social disparities (Adenle, Azadi, and Arbiol 2015; Bone et al. 2011; Kishore, Bhandari, and Gupta 2004).

To date, limited research has examined the effectiveness of climate change adaptation technologies in enhancing food security, improving livelihoods, and addressing social dynamics such as women's autonomy (for scholarship on women's property rights, food security, and the environment, see Bhandari 2017; Bhandari and Burroway 2018; Burroway 2012; Sommer, Burroway, and Shandra 2022, 2024; for cross-national studies on climate change technology see Álvarez-Herránz et al. 2017; Fatima, Yanting, and Guohua 2023; Töbelmann and Wendler 2020). This article draws on two complementary data sources from Gujarat: a quantitative survey of 199 farmers in Patan district (Harij, Sami, and Sankheswar blocks) conducted in 2024 and qualitative interviews with 48 farmers collected in the villages of Nani Chandoori and Dudhkha (in the Sami block) and Aritha (in the Harij block) in 2019. Both datasets were collected to assess the effectiveness of Bhungroo irrigation technology in improving crop yields, its role in shaping migration patterns, advancing women's autonomy, and influencing household economic conditions. We use regression analysis for the survey data and contextualize these findings through qualitative field interviews.

This article is structured as follows. First, we provide background on the development of the Bhungroo initiative. Second, we review the literature on climate change resilience and coping mechanisms, with particular attention to technologies designed for regions affected by extreme weather. Third, we describe our sample and data collection methods. Fourth, we present and analyze our findings. Fifth, we situate these findings within the broader local and global sociopolitical and economic context, framing farmers' perspectives within ongoing climate crises. Finally, we conclude by outlining directions for future research, emphasizing the importance of mixed methods in climate change scholarship.

Our research questions are as follows:

1. Can a local technological intervention help farmers increase yield for their livelihoods?
2. Can it allow villages to be more resilient to climate-related phenomena such as drought and flooding?
3. Does the intervention associated with women's autonomy contribute to better management of the land?
4. How does women's empowerment of Bhungroo ownership qualitatively affect decision-making, autonomy, and local dynamics in these villages?

Background

The Bhungroo initiative emerged from extensive work with marginalized women farmers in Sami and Harij blocks within the Patan district, where a recent earthquake in 2001 had left communities in severe hardship, with an urgent need for sustainable livelihood solutions. These regions have long faced adverse climatic conditions, marked by recurrent droughts, erratic rainfall, and flood events, leading to extensive waterlogging and crop failures. The prevailing agricultural instability forces smallholder farmers into cycles of poverty and seasonal migration, exacerbating food insecurity and reducing school attendance among children.

The 2001 earthquake, which caused widespread destruction across Gujarat, severely affected local infrastructure and livelihoods. However, through collective resilience, these communities began their recovery efforts, including housing reconstruction and livelihood restoration. Yet the structural issues of water scarcity, soil salinity, and agricultural instability continued to hinder long-term sustainability. A critical need emerged to address food insecurity in the wake of prolonged droughts (1998–2000), a situation aggravated by the earthquake's economic and infrastructural aftermath. Sami and Harij, predominantly composed of small and marginal landholders, were experiencing compounded challenges: soil salinity, prolonged waterlogging during monsoon seasons, and a lack of access to productive resources. These conditions led to reduced agricultural productivity and income, compelling farmers to migrate to urban areas for subsistence jobs, deepening poverty and negatively affecting food security.

The primary need was to alleviate waterlogging and secure a reliable water source. Under these conditions, smallholder farmers (mostly men) often became laborers for rich farmers. Moreover, while the farmers migrated for work, their wives and daughters stayed at home and, because they did not have the ownership rights, they did not have the power to make decisions about how to farm the family's plot and manage the household. In response to ongoing disparities in land ownership between men and women, Bhungroo intended to increase women's roles and improve their lives and gender relations. Taken together, the smallholder farmers needed something to improve their situation given the difficult weather patterns and the poor terrain resulting from issues related to climate change and women needed something to give them rights to the land.

Bhungroo ("straw" in English) is a water conservation technology that filters, injects, and stores excess farm water or stormwater underground for usage in lean periods. First developed in Gujarat by the social enterprise Naireeta Services in collaboration with climate-affected communities, Bhungroo is designed for regions with highly unpredictable rainfall. The system can store up to four million liters of excess rainwater during the monsoon season and later release it for irrigation during droughts, restoring soil fertility and supporting crop growth (see visual at https://mirroring-hope.netlify.app/#/). Today, there are 17 design variations tailored to different local environmental conditions. All models have a zero-water footprint, ensuring that stored water is free of sediments, contaminants, metals, and ions. Each unit can irrigate more than 25 acres annually, enabling farmers to recover the installation cost ($750–$1,000, depending on project size and location) in less than two years (Peerzada 2018). Bhungroo exemplifies the integration of indigenous knowledge with modern technology and was intentionally developed as a woman-led initiative.

Giving women rights to the Bhungroo technology was intended to expand their control over both natural resources and social environments. Through the initiative, women are trained to use, distribute, and manage the system, positioning them at the center of decision-making. Their role is therefore twofold: to support community adaptation to challenging land and weather conditions, and to determine when and where stored water is allocated. This authority not only enhances community resilience but also provides women with greater leverage within their households and broader social networks.

Although informal water rights cannot substitute for formal land rights, Bhungroo provides women with the means to make farmland productive. When women manage the irrigation technology, they gain the capacity to transform otherwise unusable land. If land ownership signifies power, then control over water represents a parallel form of power. By fostering gender equity and creating social conditions that expand women's access to land and economic resources, this technology is designed to enhance women's autonomy.

Previous Research

We begin this section by summarizing some of the academic research that demonstrates the intersectional barriers to climate change resilience. Then we discuss previous literature that points to how technologies can be useful in addressing local climate change issues.

Literature Review

Climate changes, such as the ones experienced in Gujarat, can exacerbate existing inequalities, especially on women and girls. For example, in sub-Saharan Africa and South Asia, studies have shown that to cope with extreme heat, flash floods, and cyclones, household heads often marry off their daughters early to pay for expenses from the damages (Ahmed et al. 2019; Asare and Forkuor 2024; Carrico et al. 2020; Pope et al. 2023). These daughters often experience sexual violence during the aftermath of extreme weather events, making it difficult for them to marry in the future (Pope et al. 2023). A study by Chigusiwa, Kembo, and Kairiza (2023) found that in Zimbabwe, drought and social conflict affect women and girls more substantially than their male counterparts. Similarly, in Ghana, researchers find that flooding affected people differently depending on existing assets, inequalities, and gender (Afriyie et al. 2016).

Research also suggests that climate change may hinder efforts to achieve gender parity in land ownership. Across parts of Asia, studies show that typhoons, heavy rains, and droughts can trigger social conflict and infrastructure collapse, effects often compounded by weak governance (Delina and Cagoco-Guiam 2018; Mangada and Cuaton 2022; Sarbahi and Koren 2022; Sekiyama 2022). Unfried, Kis-Katos, and Poser (2022) further demonstrated that water scarcity can more than triple the likelihood of conflict.

Climate change also threatens food security. Studies indicate that it drives displacement, increases migration, and exacerbates challenges related to disease and nutrition (Hoffmann 2022; Serdeczny et al. 2017; Wolde, D'Odorico, and Rulli 2023). These impacts disproportionately affect poorer rural households compared with wealthier ones (Becchetti, Castriota, and Conzo 2017; Cassar, Healy, and Von Kessler 2017; Gummerson et al. 2021; Kurosaki 2017; Lynham, Noy, and Page 2017; Mirzabaev 2015).

Water access is an ongoing issue for many regions of the world experiencing climate change issues, including India. For example, in Gujarat, because of overexploitation of groundwater, in 2003, 57 subdistricts were demarcated as dark zones, which banned further extraction of groundwater and new electricity connection for agricultural purposes (Bahinipati and Viswanathan 2019). The study demonstrated that along with loss of harvests and farmer income, water scarcity also threatens intra- and intergenerational water and food security. Bahinipati and Viswanathan (2019) also found that although there are various agricultural interventions in action, such as subsidies for microirrigation technology adopters and lifting the electricity connection ban, there is a need for more studies assessing the impact on farmers' climate technology adoption behaviors.

Studies that have addressed farmers' adoption behavior for climate change technologies concerning water within this region have shown that the populations' perception of risk as well as traditional practices and environmental beliefs are major influences (Jayakody et al. 2024; Manzo and Devine-Wright 2013; Singh, Osbahr, and Dorward 2018). Research has also pointed out that although science can provide the tools and technologies to manage resources, it is essential to understand how water scarcity is perceived by the local culture, as these insights can help explain investment decisions, contribute to adaptive behaviors (Alam, Alam, and Mushtaq 2017), and aid in the cocreation of projects designed for natural resource management and livelihood adaptation situated within the local region (Tye and Suarez 2021).

One proposed solution is the introduction of technologies to help communities adapt to and mitigate the impacts of climate change. Although cross-national studies show mixed results (Álvarez-Herránz et al. 2017; Fatima et al. 2023; Töbelmann and Wendler 2020), scholars have also highlighted the environmental harms associated with technological development (Clark et al. 2023; Foster et al. 2021; Stuart et al. 2020) and offered critiques of "techno-optimism" (Adenle et al. 2015; Bone et al. 2011; Kishore et al. 2004).

Nevertheless, evidence suggests that climate adaptation technologies designed with local conditions in mind can play an important role in helping smallholder farmers cope with extreme weather events.

Situated Sustainability

When are climate change technologies effective? Previous research in the field of sustainability studies indicates that strategies must fit the local context to be beneficial to people and the environment (Deb and Haque 2017; Khan et al. 2004; Kihila 2018; Mah et al. 2020; Shuaibu et al. 2014; Tashmin et al. 2018). We use Sze et al.'s (2018) concept of a *situated sustainability* to further articulate the importance of context when concerning climate change technologies. There are several ways the Bhungroo technology fits into a situated sustainability framework (Sze et al. 2018). This framework draws from sustainability and sustainable development and emerged from environmental justice research. It centralizes issues of gender, race, and indigeneity and gestures toward anti-capitalism. These centered issues help eliminate reinforcing ideologies that produce social injustice and environmental harm by rejecting the idea of simply greening the current business as usual (Clark et al. 2023; Foster et al. 2021). It does so by having an awareness of the ways sustainability is deployed in political and social life and investigates the fundamental political conditions that have caused a disproportionate distribution of climate vulnerability. Situated sustainability addresses the politics, histories, displacement, violence, and other roots that created the current socially unjust and environmentally unstable circumstances.

One major component of Sze et al.'s (2018) work is that it acknowledges that those from differently positioned social groups cannot know or assign meaning to ecology or sustainability for other groups. This is because different regions are shaped by different geographies and social and cultural factors, such as race, class, gender, ethnicity, age, and ability. Sustainability must be situated according to the local needs of the community, and a framework for one region will not fit another. The situated framework relates back to *situated knowledges* by Haraway (1988), which states that situated knowledges are about communities and not the individual. Situated sustainability calls for the decolonization of the curriculum of sustainability studies, as the structure of colonization fragments and destroys systems.

In his chapter "Situated Urban Drought Resilience," Baker (2018) discussed the basics of drought resilience within situated sustainability. Drought resilience is situated within wealth, as resilience to droughts requires both adaptive physical and social infrastructures. According to Baker, the capacity to endure a drought is based on two processes: robustness and resilience. *Robustness* refers to the capacity to remain constant during environmental stress, while *resilience* refers to the ability of a system to recover from stress. Together, this makes drought a socioecological problem.

In an arid region such as the northern part of Gujarat, the lack of rainfall in the dry season means there is not enough water for basic needs and services, which makes identifying and implementing a form of water storage essential. Regions with high aridity and minimal infrastructure are the most vulnerable. Drought is an important ecological stressor because it severely disrupts the functioning of a socioecological region, and its ability to prepare and respond depends on its economic capacity. In wealthier countries, droughts cause economic damage; in contrast, in poorer countries, droughts cause death, which is why those in the frontlines of climate change need the autonomy to choose their local solutions. As per capita income increases globally, wealthier citizens use more water, and this puts more stress on water systems for everyone, especially the poorer citizens.

Addressing drought requires transdisciplinary collaboration and the co-production of actionable knowledge with local communities. Building resilience depends on accounting for temporal and spatial factors, ensuring that water governance is scaled appropriately to available resources and population needs. Yet at the international level, most water treaties fail to explicitly address drought, even though water allocation remains a central source of conflict (Giordano and Wolf 2003). As Baker (2018) noted, "in the Global South, multisector, community-level water planning may be more realistic than Western-style, top-down planning" (p. 139). Further complicating governance, external actors such as the World Bank frequently shape water policy, often with outcomes that are misaligned with or detrimental to local needs.

For example, according to a recent news article in *Al Jazeera*, conflicts between Pakistan and India have arisen since the 1960 Indus Waters Treaty, facilitated by the World Bank, that divided six rivers shared over international boundaries (Hussain 2024). This is the only water treaty on earth that divides bodies of water rather than shares them. The rivers that India controls—Ravi, Sutlej, and Beas—have less water than the three given to Pakistan. India has access to only 20 percent of the water allotted from the treaty, which is a major problem as the most populous country in the region. India wants to renegotiate the agreement because the treaty does not take into consideration the current effects of population stress and climate change. To mitigate water scarcity, India has built an infrastructure to control more of the waters, which is contested by Pakistan. In 2022, to facilitate the dispute between India and Pakistan, the World Bank appointed a neutral expert and allowed proceedings at the Permanent Court of Arbitration in The Hague, the Netherlands.

This situation highlights the importance of a situated sustainability. For instance, the static nature of treaties leaves little room for negotiation and does not consider unforeseen challenges, such as drought accelerated by climate change. As mentioned by Baker (2018), outside actors such as the World Bank have significant influence on water governance, which does not always lead to a positive outcome. In this case, the World Bank is an outside actor that negotiates the decisions for two countries that are made up of differently positioned social groups. The need for situated sustainability to alleviate the conditions of water scarcity is historically better governed by local initiatives within the region (Baker 2018; Bryant and Bailey 1997; Peet 2003).

In contrast, the Bhungroo technology is situated as a sustainable solution within the region in specific Gujarat farming villages. The technology was developed with involvement from the farmers in these villages and designed specifically to help meet the needs affected by climate change. As mentioned, instead of overcoming the major barrier of land ownership, the system was designed to be owned by women and used by small landholders.

On the basis of this previous research, our hypotheses are as follows:

> *Hypothesis 1*: The use of Bhungroo technology improves crop yields, independent of farm size or local weather conditions.
>
> *Hypothesis 2*: The use of Bhungroo technology increases farmers' resilience to climate-related events such as droughts and floods.
>
> *Hypothesis 3*: The use of Bhungroo technology provides women who manage it with greater autonomy and decision-making power within the household.

Data and Methods

Mixed Methods

We draw on two primary data sources: a local quantitative survey and 48 in-depth interviews supplemented by participant observation with farmers in situ. First, we describe the quantitative data collection, analysis, and findings. Then we detail how the qualitative data were collected and provide quotations and insights from these data in an effort to situate the quantitative findings within its social context as well as to provide potential mechanisms to explain the quantitative findings (Strijker, Bosworth, and Bouter 2020). Using mixed methods allows the findings of the two analyses to contextualize and support the findings of the other. The quantitative data show the direct measured impact of Bhungroo on crop yields (the main source of income and well-being for these farmers) and the interview and participant observation provides insight into the potential mechanisms for these yield gains as well as provides a glimpse into the emotional and societal impact the technology may have through being associated with women's ownership and control of the technology. The qualitative analysis also demonstrates how knowledge of local climate and customs contributes to the success of climate adaptation solutions.

Quantitative Methods

Sampling Strategy. The Naireeta team collected survey responses across three talukas (blocks) in Patan district—Harij, Sami, and Sankheswar—to ensure diverse geographical representation, including areas with high, low, and minimal rainfall inundation during peak monsoon periods. Respondents included both Bhungroo users and nonusers. Efforts were made to capture variation across caste groups and broader social dynamics within the region. Village selection also accounted for distance from key infrastructure, such as highways and taluka headquarters, to assess how proximity influences state administrative responsiveness over time. In addition, the field team emphasized the role of political leadership and local opinions of leaders, noting that villages with politically influential figures often secure greater access to state resources, whereas those without such leadership are more likely to face marginalization. This sampling strategy was designed to reflect these complexities, producing a dataset that offers a comprehensive view of community dynamics and the broader sociopolitical context in which development programs are implemented. We review each taluka in detail before outlining the methodology used to analyze the survey data.

Harij Taluka, located approximately 10 km southwest of Patan in Gujarat, is a predominantly agricultural, semiarid region with flat, low-lying terrain at an average elevation of 50 m above sea level. The climate is characterized by hot summers reaching up to 44°C and mild winters around 15°C to 20°C. Monsoon rains are crucial for the region's agriculture, although erratic rainfall often leads to droughts, affecting crop yield and economic stability. Agriculture forms the backbone of Harij's economy, with major crops including castor, cotton, millet, Indian gram, cumin, and wheat. Although crop production relies primarily on monsoon rains, some areas use canal or well irrigation, supporting dryland farming practices on variable soils. The community is largely rural, comprising diverse social groups engaged in farming and small-scale businesses. Economic development is modest, as limited infrastructure and employment opportunities outside agriculture present challenges for many residents. The villages sampled in Harij Taluka are presented in Appendix 1.

Sami Taluka, in the Patan district of Gujarat, is a semiarid, rural region marked by extreme temperatures, with hot summers and cool winters. It experiences low and irregular rainfall, often insufficient for agricultural needs, leading to frequent droughts. The area's soils are predominantly sandy and loamy; however, salinity issues are prevalent in areas with extensive groundwater extraction, which has also led to depletion. The geology is largely alluvial, affecting the soil's water retention capabilities. Groundwater serves as the primary source for drinking and irrigation, with limited surface water availability, making efficient water management crucial. The region's agriculture relies on drought-resistant crops such as bajra (pearl millet), wheat, cotton and castor oil seeds. Water scarcity restricts crop variety and yields, affecting the income stability of local farmers. Sami's economy is heavily dependent on agriculture, with limited alternative employment options. The community is composed of agrarian castes and marginalized groups, many of whom practice subsistence farming. Environmental challenges—drought, water scarcity, and soil degradation—pose significant barriers to sustainable agriculture, underscoring the need for effective water management and alternative livelihood initiatives to bolster resilience. The taluka is badly hit by seasonal precipitation inundation for a period of 1 to 3 months during peak monsoon period. The villages sampled in Sami Taluka are available in Appendix 2.

Sankheswar is a taluka in the Patan district of Gujarat with a semiarid climate that is significantly influenced by its geographical and geological characteristics. Located in northwestern Gujarat, this region experiences extreme temperatures, with hot summers, mild winters, and erratic rainfall during the monsoon season. The area's annual average rainfall generally is low, which affects water availability and agricultural productivity. The soil in Sankheswar primarily is alluvial and sandy loam, with certain regions experiencing salinity due to saline groundwater. Despite the soil's moderate fertility, the combination of limited rainfall and salinity hinders crop yields, making irrigation a crucial resource for farmers. The geology of the area is marked by alluvial deposits and occasional sandstone, typical of northwestern Gujarat's flat terrain. Groundwater is the primary water source, though its availability is limited and often saline. Consequently, water scarcity is a pressing issue, affecting both agriculture and drinking water supplies. Agricultural practices in Sankheswar primarily involve growing staple crops such as millet, wheat, and castor, which are relatively drought resistant. However, limited irrigation infrastructure restricts crop diversification. The economic structure of the area leans heavily on agriculture, with small-scale industries also contributing to livelihoods. Communities here are diverse, including marginalized groups who rely on subsistence farming. These communities face recurring challenges related to water scarcity, soil salinity, and economic vulnerability, which are exacerbated by weather variability, particularly drought and seasonal inundation due to surface water flow. The villages sampled in Sankheswar Taluka are shown in Appendix 3.

Sample. The previous section outlined our sampling strategy. Here, we discuss the strengths and limitations of the sample and explain our choice of statistical methods. The team sought to include as many farmers as possible within the study area, resulting in a sample of 199 farmers. This sample reflects a substantial effort by local experts to capture variation in climate, terrain, caste, politics, and community dynamics. Considerable care was taken to ensure diversity and inclusivity. To date, this dataset represents the only comparative quantitative evidence in the region on farm yields, demographics, and Bhungroo adoption. As such, it marks a significant step forward in evaluating the effectiveness of Bhungroo technology and provides an important complement to existing qualitative research on the local impacts of climate adaptation tools.

However, the sample is not without limitations. Although great care was taken to ensure a random sample, this was limited by the sample frame and the population of farmers that have received the Bhungroo technology. Additionally, as the data are hyperlocal, it is not possible to generalize outside of the Patan district in Gujarat with these data. Our data are generalizable to the extent to which people in Gujarat who have similar farms will expect similar outcomes. Our study is not meant to be generalizable outside of the study area. Put differently, although there is some generalizability to populations that are similar in the same region, care should be taken when doing so.

We report descriptive statistics in Table 1. The dependent variables of interest (i.e., total yield and yield by area) are interval ratio–level data. The independent variables are all ordinal level variables, except for sex, and whether the farmer has the Bhungroo technology, which are nominal (dichotomous). To begin testing if there were any potential associations in the data we calculated means differences. We ran an analysis of variance between the dependent variables and the independent variable of whether the farmers have the

Table 1. Descriptive Statistics for 199 Farmers in Gujarat.

	Definition	Descriptives
Dependent variables		
Yield	Total yield, measured in mann	
Mean		366.63
SD		236.40
Yield by area	Total yield divided by total land area for a measure of productivity per bigha	
Mean		29.38
SD		15.65
Independent variables		
Bhungroo	Dichotomous variable indicating whether the respondent has Bhungroo	
Have Bhungroo		50%
Do not have Bhungroo		50%
Education	Ordinal variable indicating the level of education the respondent has achieved	
No formal education		14.5%
Primary school		38.5%
Secondary school		34%
High school or higher		13%
Farm size	Ordinal variable indicating the size of the respondent's farm	
<1 bigha		10.5%
1-5 bigha		61%
>5 bigha		28.5%
Sex	Dichotomous variable indicating the respondent's sex	
Male		56.5%
Female		43.5%
Age	Ordinal variable indicating the age of the respondent	
18-30 years		18%
31-45 years		70%
46-60 years		11.5%
≥60 years		0.5%
Family size	Ordinal variable indicating the size of the family (number of individuals in the household)	
1-5 individuals		87.5%
6-10 individuals		12%
>10 individuals		0.5%

Bhungroo technology, which indicated that there was a statistically significant difference at the .01 level. However, we wanted to determine if other variables were relevant to the dependent variables and we wanted to be able to hold those constant while testing the relationship, so we decided to use an ordinary least squares regression analysis. We describe our statistical analysis and the regression assumptions associated with it in the next section.

Statistical Model. We analyze the data described in the previous section using ordinary least squares regression in Stata 14. The regression equation is denoted by the following formula:

$$y_i = a + b_1 X_1 + b_2 X_2 \cdots + b_k X_k + e_i,$$

where y_i is the dependent variable for each individual, a is the constant, b_1 to b_k are unstandardized coefficients for each independent variables, X_k are independent variables for each individual, and e_i is an error term for each individual.

To ensure that we are not violating typical regression assumptions, we first calculate the mean and highest variance inflation factor scores for each model. There do not appear to be any potential problems with multicollinearity with mean and highest variance inflation factor scores not exceeding a value of 2.5 in the models (Tabachnick and Fidell 2019). Second, we use Stata 14's ladder and gladder commands to determine if a variable is normally distributed or needs to be transformed. The ladder command reports a χ^2 test for eight different transformations. The null hypothesis for the χ^2 test is that a specific transformation approximates normality, if the χ^2 statistic is statistically significant, then we reject the null hypothesis and conclude that the specified transformation does not approximate normality (Tukey 1977). We confirm the statistical tests by visually inspecting graphical distributions for each variable using the gladder command. We transform variables on the basis of the results of this procedure and note them in the description of the measures above. Third, we calculate standardized residuals to determine if outliers are a problem. We do not find any multivariate outliers because no standardized residuals exceed an absolute value of 2.5. Fourth, we calculate Breusch-Pagan heteroskedasticity tests for each model. The null hypothesis for this χ^2 test is that the error variances are homoscedastic or equally distributed (Tabachnick and Fidell 2019). The coefficients for the χ^2 statistics reach a level of significance in every model. As such, it appears that we may have problems

Table 2. Ordinary Least Squares Regression Estimates.

Independent Variable	Model 2.1 Total Yield	Model 2.2 Yield (per Bigha)
Bhungroo	80.088*	6.359**
Education		
Primary school	77.525*	10.303**
Secondary school	13.600	2.931
High school	13.897	6.333
College	49.423	4.378
Cultivated land area of the farm	22.110***	
Sex (1 = woman)	−29.673	−.273
Age		
31–45 years	−5.712	2.205
46–60 years	−43.854	−1.126
≥60 years	−50.450	−6.523
Farm size	−4.525	−3.117
Family size	17.784	−3.786
Constant	39.442	30.495**
R^2	.529	.115
Sample size	199	199

*$p < .05$. **$p < .01$. ***$p < .001$

with heteroskedasticity. We report robust standard errors to address this issue.

Quantitative Findings

In Table 2, we present the ordinary least squares estimates of total yield. The number presented is the unstandardized coefficient. We report one-tailed significance tests at the $p < .05$, $p < .01$, and $p < .001$ levels because of the directional nature of our hypotheses. Let us begin by considering the Bhungroo irrigation technology variable. The coefficients that represent having Bhungroo are positive and statistically significant. This finding suggests that having Bhungroo is significantly associated with both total yield and yield (per bigha) increases.

On average, holding everything else constant, farms with Bhungroo can be expected to have an increase in yield of 80 mann, or 1,600 kg (1.6 metric tons). This is an increase of about 22 percent from the mean yield of the sample of 366 mann, a significant improvement for farmers relying on their crops for their ability to provide for their families. This trend holds when we control for the size of the farms as well. In model 2.2, the coefficient for Bhungroo on yield (per bigha) is 6.359, indicating that for every bigha (a unit of measurement equal to approximately three fifths of an acre in the region of study), there is a corresponding increase in yield of 6.359 mann (or ~127 kg). Similar to total yield, this represents an increase of about 22 percent from the mean yield per bigha of the sample. Stated plainly, farmers who have Bhungroo can expect between a one fifth and one quarter increase in their total productivity with no other changes. Turning to other findings, we control for total farm size in model 2.1 to prevent overinflated coefficients. As expected, larger farms were associated with higher yields. This is no surprise as larger farms can plant more crops. In our sample of 200 farms, we find no significant association between age, sex, or family size on the yield of crops. The significant findings of Bhungroo considering the lack of significance of these family demographics may indicate the helpfulness of Bhungroo to farmers despite any differences in who is running the farm. The final quantitative finding that we would like to discuss is education.

We find an interesting pattern that farmers with primary schooling, but not those with higher levels of education, have significantly higher yields than farmers with less than primary education. Although this may at first seem surprising, as we would expect yield to continue to increase with increasing education, this could be explained by cultural differences in the region. Actually, the education system (primary or higher secondary) in India does not teach any skill or knowledge related to agriculture. However, there is a specialized course available in the agriculture sector from undergraduate and postgraduation level, and our findings are not statistically significant for college level education either. What, then, could account for primary education being the only statistically significant level of schooling?

There is evidence from previous theory to suggest that those with primary schooling know farming, and so they invest in that, while those with higher levels of education may go to work beyond the farm. We also know from previous research, and the qualitative data described below that floods and droughts affected the closing of schools, which made it more difficult for girls to travel to school after 12 years of age because of the danger of traveling long distances and being accosted. Our data, however, are on farmers, not their children. Therefore, we cannot relate education with leaving the farm. As further detailed in the following qualitative sections, because of the Bhungroo, many children could have access to better education from their parents, so future research could be done to better understand the well-being of the children of the generation that received the Bhungroo technology. Thus, although this reasoning does provide some context for this finding, future research is needed to more fully understand it.

Qualitative Methods

Although our quantitative data analysis was useful in testing the impact of the Bhungroo technology on crop yields, it does not reveal the mechanisms for how it affects crop yields, as well as does not provide the larger context for why the technology is relevant and successful. Thus, we believe that supplementing our quantitative analysis with qualitative data could provide some clues to the mechanisms of higher crop yields from Bhungroo and clarify why the Bhungroo technology has such success locally where other more top-down strategies have been less successful.

The qualitative data used in this project were initially designed as an exploratory phase to identify relevant variables, farmer perceptions, and context-specific challenges. These insights directly informed the development and framing of the 2024 survey instrument used in the quantitative analysis of this article. Although we drew on qualitative findings to help contextualize the quantitative data, the two datasets were not triangulated for concurrent interpretation. Instead, the 2019 data served a developmental purpose within a sequential mixed-methods design. To reiterate, these interviews were collected in 2019, which is several years prior to the quantitative data collected in 2024. In this initiative, our team aimed to hear the voices and experiences of 48 farmers across three villages, Nani Chandoori, Dudhkha, and Aritha, represented in Appendix 4. Twenty-one farmers in Nani Chandoori and Dudhkha (12 women and 9 men) received the Bhungroo technology, whereas 27 farmers in Aritha (15 women and 12 men) did not. Of those who had received Bhungroo, 13 of 21 farmers were literate. Of those who had not received Bhungroo, 10 of 28 were literate. The farmers we interviewed were between the ages of 21 and 60 years.[1]

To understand how the Bhungroo technology affected people within these villages, we interviewed farmers who had and those who had not received the Bhungroo technology. Interviews were carried out over a two-day period in the villages. The main investigators split into two teams to carry out the interviews and each had a local translator led by Naireeta Services. The discussions were guided by open-ended questions focused on what the farmers experienced, what they did when there was no farming work, and how or if the Bhungroo affected them. In the next section, we provide an analysis of the trends/themes that were observed from this research, supported by quotations from the interviews in a narrative form, to give a sense of the larger context in which the Bhungroo technology is located, conceptualize the mechanisms that could contribute to the positive quantitative findings regarding the Bhungroo technology, and point toward any clues for how the Bhungroo project could further evolve to meet the needs of the population. Our first three themes discussed below include farmers' experiences with severe weather events, family changes, and income issues that often were related to such events, especially in the absence of Bhungroo technology. These themes emerged from farmers who, at the time of the interview, did not have the Bhungroo technology. The final two themes, cohesion with community and financial benefits, are reflections of those who had the technology at the time of the interview.

Qualitative Findings

Experiences with Severe Weather Events. The first theme that emerged from the interviews and participant observation was the severe impact of climatic changes and extreme weather events on farmers in Gujarat. Recurrent floods and droughts have led to declining soil quality, water scarcity, crop destruction, reduced harvests, and widespread displacement. Severe floods not only destroyed homes, forcing families to seek temporary shelter in schools and other facilities, but also washed away topsoil and vital nutrients, leaving farmland infertile and limiting viable settlement areas. Although some families managed to remain in or return to their homes, drought conditions continued to restrict farming capacity and reduce irrigation water, leading to repeated crop failures and financial hardship. As one farmer explained, "All the crops were destroyed in the fields. . . . Then, in the winter, we got water from the canals. But it's getting worse as the days go by. Water is getting less and less."

Families usually work together and live on their farms or live nearby their family's farms. Changes in weather patterns thus tend to affect the day-to-day life and well-being of generations of families. For example, one farmer described the effect these disasters had on his extended family: "My family, including my two daughters and their husbands, were productive—growing cotton, wheat, and cumin—until water scarcity made farming difficult. When the floods came, we suffered great losses. All the grains were destroyed."

For communities in remote villages far from towns and cities, accessing essential resources during climate-induced scarcity is often difficult. Geographic isolation also limits the reach and effectiveness of government interventions aimed at mitigating climate impacts. As one farmer explained, the absence of state support not only deepened hardship but also fueled social tensions: "The government didn't help us at all. Because of that, people started robbing each other. Those

[1]Literacy was determined by individuals who signed their names on the interview release form. We made the assumption that those who used a thumbprint stamp were not literate.

who didn't have enough water and food started to raid the houses of those who are assumed to have money."

Resource scarcity and the need to seize goods from households perceived to have more can destabilize communities, undermining collective efforts to cope with and recover from climate-related crises. Some families sought alternatives by selling personal possessions to generate income. As one farmer explained,

> I would never ask for money from anyone. During the flood, I had to sell some of my personal belongings, like jewelry, and even one small sheep. I used the money for household items, for medicine for the kids when they get sick, and for groceries, little by little.

Generally, families had economic difficulties recovering from loss due to the severe weather events (e.g., destruction of crops or homes). Unpredictable weather cycles, including droughts and floods devastated agriculture. The reduced water availability produced minimal crop yields which contributed to economic instability. The next section helps further elaborate on the impacts of these climate changes by discussing a major theme in the interviews: changes within families.

Changes within Families. Before the recent increase in severe weather events, farmers sent their children to school, families relied upon women to help farm the land, and elders made key decisions relating to long-term financial planning. However, with the increased frequency of floods and droughts, there were higher levels of school dropout rates, increasing domestic violence against women, lack of attention to women's contributions to the family, keeping women out of the public sphere, concentrating resources among male heads of households, disempowering and discounting the knowledge and experience of elders, increasing cross-generational poverty, decreasing education for children, relinquishing educational opportunities for women, and increasing barriers to women's leadership.

Several farmers described how family life had changed with recent climate issues. As mentioned, families tend to work and live on their own farms, but with lack of water for crops, many had to change their way of life. One farmer stated, "My wife and I have to work on someone else's farm and are unable to tend to our children."

The ability to go to school was often brought up in our interviews. In part, this was due to the lack of resources the family had to send them to school. One farmer did not allow any of her six children to go to school and instead sent them out to find work. She said, "As day laborers, we live a hand-to-mouth existence, and hope for two or three days of work a week."

Many adolescent boys could not attend school because their families could not afford it. Additionally, some boys dropped out of school because of economic pressures or family duties. Sometimes their idleness created social issues for the community. This issue was even more pronounced for girls. Farmers often made the decision to send boys to school but not the girls. When schools are far away, some farmers made the choice not to send their girls back to school. For example, one farmer said, "My two sons are in school, but my daughter couldn't continue because there were no schools for her in the nearby village."

This decision can give some context to gender disparities in the region. Resource scarcity and the need for labor help explain why some daughters are not sent to school. Although women are generally expected to manage household responsibilities, economic pressures often force them to work outside the home, leading families to withdraw girls from school to take on domestic duties. As one farmer explained, "[My daughter] had to drop out of school and take care of the household while we were away at work."

Several factors—including resource scarcity, the need for children to contribute to household labor, and the distance to schools—contribute to gender disparities in education. Parents often expressed concerns about girls traveling long distances, citing risks to their safety. The closure of nearby schools, whether due to resource shortages or climate impacts that damaged facilities, further limited educational opportunities. As one farmer explained,

> As a young girl, I was not allowed to go to school. Now, my daughter, who is 12, also is not allowed to attend school beyond the sixth grade. Because of "love affairs" as they grow up, we're scared. We used to send our daughter to school in the village, which was up to the sixth grade.

Climate change, particularly the water crisis, has affected families across generations. Elders, traditionally respected as household decision-makers, often found themselves disempowered by the scale of climate-related disasters. As a result, younger family members were sometimes forced to assume responsibilities that would normally rest with older generations. One farmer explained, "Even though my in-laws are still alive, they were traumatized by the water crisis. My husband and I reluctantly took over managing the family's finances and our children's education, which left my in-laws feeling useless."

Overall, climate changes seemed to affect family systems, with family members taking on other roles for those that had to go to work. Worsening environmental conditions seemed to exacerbate cross-generational poverty. Although these changes shifted family dynamics, inequalities between boys and girls were exacerbated, resulting in girls not being able to go back to school so they could take on other roles. This change was also justified by the far distance from schools being particularly dangerous for girls. If families are unable to afford or send children to school, particularly girls, this could limit future opportunities and perpetuate social inequality. Women, particularly those in rural areas, often are excluded from education, hindering their ability to improve their social and economic status.

Income Issues. We find that a major driver of altering behaviors in family life as a result of climate change is the ability of farmers to become financially stable. Farmers reported not being able to save money to deal with future disasters, and their vision of owning their own land, which had been a source of pride for small holder farmers, was no longer seen as possible. Several farmers discussed their frustrations with being unable to change their financial situation. One farmer said, "I no longer have any hope of owning land. My only source of income is through manual labor."

Confronted with the "new normal" of severe weather events, many farmers no longer expected consistent financial gains and instead turned to loans that proved difficult to repay. In some cases, this reliance exposed families to predatory lending practices. As one farmer recounted, "My family borrowed money from a moneylender who charged 36 percent."

Farmers discussed how they struggled to repay government loans after their agricultural income was wiped out by floods or droughts, leading to further financial hardship. Farmers often depleted their savings to cover debts and expenses and had little ability to invest in future opportunities. Families tended to rely on irregular day labor for survival, facing severe economic insecurity. One farmer explained, "We must do manual labor for 10 to 20 days a month to make ends meet. And we still take out loans."

Climate change has made farming increasingly unpredictable, resulting in unstable or delayed financial returns. Many farmers reported having no savings and living paycheck to paycheck. Instead of relying on their own harvests, some turned to buying vegetables from the market to resell as a means of survival. As one farmer explained, "I have to buy vegetables from the market and upsell them to others. There are a lot of financial difficulties. We earn and spend money. There is barely any savings."

Many families realized that they may never be able to own land or make their land useful again. It was also clear that, from their experiences with government and other loans that they were hesitant to invest in technologies, especially given existing debts and fears of further financial loss. The next two themes highlight the experiences of those who did invest in the Bhungroo technology.

Cohesion within Communities. Prior to creating the Bhungroo technology, the founders of the technology, Trupti Jain and Biplab Paul, witnessed the way women struggled to gain recognition for their work. They were aware that introducing Bhungroo within a patriarchal system would only be effective if it benefited the community: by providing opportunities for idle youth, reducing the amount of time women spent on gathering water, and increasing women's and men's self-esteem. From our interviews, it appears that giving Bhungroo ownership to women enhances their control over resources and strengthens their role within the family and community, countering patriarchal norms. For example, one farmer spoke about how her family adjusted to the new irrigation system:

> "I used to work on a dairy farm, and my husband had to migrate to find ork. Now we farm our own land, and I decide how to use the money. Maybe we will get electricity next year but, for now, we get enough water for bathing—our bucket is full. We don't need bathrooms, and we have enough money. Before I used to walk miles to get water but now, I have more time to do my work and help others.

Farmers also reported gaining increased self-esteem and social recognition. One farmer discussed that, with Bhungroo, his family grows a variety of crops, such as cotton, castor, gram lentils, Indian Plantago, cumin, and others. He said, "My basket size has increased 8 times. And, as the family's financial situation got better, my father stood for the village election, and he is head of the village right now."

It is interesting that he talks about his father's success being elected as village head in connection with the benefits his family felt from the technology. Farmers also noted how the technology provided education and technological skills to youth, which could contribute to job opportunities and increase community involvement. This included training adolescent boys to collect soil salinity data and assist with installing the Bhungroo technology.

Respondents discussed how the technology helps provide a reliable water source (especially for those who lost access to shared wells), which may contribute to women's autonomy. With a reliable water source, women farmers can devote more time to their own work, which could help with personal fulfillment and broader social impact. One stated,

> We used to take animals to the lake to drink water, which was very far. Now we have bathrooms because we have water. I don't have to walk as far to get water and I'm able to get milk

> from the buffalo to make ghee. And, when I sell the ghee, I get to keep the money. Grandfather has all the other money, and he makes the decisions.

Despite ongoing patriarchal norms, women farmers seemed to feel proud of their contributions to household welfare and their community. Moreover, farms' being productive allowed families to stay home and not migrate into the city or nearby farms to work. This may have an impact on girls' and boys' ability to attend school, as they are not needed to tend to the family or to find outside work when their farm is productive.

Financial Benefits. The research also underscores how Bhungroo not only offered economic relief but also generated important social benefits. Although ownership and operation of Bhungroo typically rest with women, decision-making power over family finances and farm management often remains in the hands of male patriarchs. Even within this context, however, Bhungroo created new spaces for women's autonomy, particularly in terms of mobility and community participation. As one woman farmer explained, "With small improvements, I can decide how to manage the household. I have time to help others in my community. I am planning to start my own small business to knit clothes and sell them in the village."

Our respondents reported that the technology helped farmers acquire new skills (such as technology adoption and improved farming practices), which led to increased productivity and long-term economic success. For instance, one farmer stated,

> Before Bhungroo, we didn't have anything. Now, I have a tractor and two vehicles (bikes), and some gold and money saved. I plant four crops in three different seasons and have ample access to clean drinking water for my family and our cattle.

With more time and resources, women started their own small businesses such as knitting and selling clothes, and many improved their household income and created economic opportunities for others. For example, once their family recovered financially using the Bhungroo technology, one farmer decided to reach out to her community: "We donate money to the temple and pray for our family's wealth and happiness."

Bhungroo reduced manual labor and costs, freeing up funds that can be used for other essential needs, such as paying off loans or investing in further agricultural improvements. One farmer mentioned how his improved financial situation led to greater respect in the community: "Now everyone can use Bhungroo and they know I have money, so they all talk to me nicely and respect me."

In sum, the one-on-one interviews revealed both the social and financial benefits farmers gained from Bhungroo technology, with women farmers in particular reporting an expanded role in household and economic decision-making.

Mixed-Methods Findings

Taken together, our quantitative findings suggest that the Bhungroo technology is associated with higher crop yields (the main source of income in these communities), while our qualitative analysis provides insights as to how the Bhungroo technology affected the lives of the farmers. In our interviews the farmers often mentioned how the technology made their lands usable again and increased crop yields, but also how the economic and social benefits of the technology were felt in their own and others' experiences. In particular, the data suggests that the Bhungroo technology addressed family and community issues while also addressing issues of income needs. These findings may provide support for place-based culturally sensitive solutions to climate adaptation. A large part of the success of Bhungroo is its ability to empower local farmers by respecting their needs and their desires. Tying this place-based eco-friendly solution to women's agency has improved family dynamics, facilitated the ability to reinvest in education, and freed up time for the development of new streams of revenue for the farmers that use it.

Our qualitative analysis provides insights into how the Bhungroo irrigation technology improved access to water and reduced the need for farmers to travel long distances to collect water. When needed, Naireeta Services involved youth in learning skills related to agriculture and technology, creating employment and educational opportunities. In addition, through one-on-one interviews with the 48 Gujarat farmers, we learned that the Bhungroo technology reduced manual labor and financial costs (e.g., it enabled a farmer to qualify for a tractor loan) and provided a more efficient irrigation system. In cases of increased water demand, expanding the Bhungroo system ensured continued success in water management.

The shift in ownership of Bhungroo to women enabled them to take control of critical resources, giving them more power within the family and community. In essence, the system recognized rural cultural norms (e.g., women's cultural obligation to stay at home) while providing solutions that respect these values. This enabled women farmers to increase their visibility, autonomy, and status in society, and helped break traditional gender barriers.

The Bhungroo technology and the built-in social initiatives developed a collective community, fostering solidarity and mutual support among farmers, especially women. Many women felt more empowered after using Bhungroo, seeing improvements in both their economic status and personal sense of accomplishment (e.g., feeling proud of their contributions and being recognized by their families).

Furthermore, because Bhungroo is a locally developed and community-run solution, farmers place greater trust in it, which facilitates more effective training and faster adoption. The founders and volunteers share the participants' lifestyles, language, and values, creating cultural alignment that strengthens this trust. In addition, Bhungroo generates spillover benefits for entire villages, making its effectiveness visible and reinforcing both community confidence and social stability. Although no technology can resolve the complex social, economic, and ecological challenges of climate change, the place-based, context-specific design of Bhungroo appears to be a key factor in its success in Gujarat. Expanding the use of this technology with foreign aid in other regions could further test and advance our understanding of Bhungroo as a scalable, place-based climate solution.

Discussion and Conclusion

In this article, we bring together two main data sources, one being more quantitative, survey data, and the other primarily qualitative, consisting of interviews and participant observation. Given our data, farmers with Bhungroo have an average of 27 percent higher total yield and 19 percent higher yield per bigha. This suggests that having the Bhungroo increases crop yields, which can help with food security and increasing income by selling surplus crops. Moreover, the mean level of satisfaction among respondents with the technology is 4.84, with 85 percent of families rating their satisfaction as a perfect 5. These results indicate that people are satisfied with Bhungroo. Furthermore, 100 percent of families responded that they received social benefits, social upliftment, and environmental benefits from the technology. Finally, 94 percent of farmers without Bhungroo report problems with cultivation of their crops, and only 27 percent of farmers with Bhungroo report the same problems.

Our qualitative research with farmers in Gujarat indicates that, despite Bhungroo's potential to uplift women farmers from impoverished families, it has not been a panacea for the problems of endemic poverty and female subordination. The interviews reveal that climate change leads to unstable family structures and thus requires intergenerational cooperation between women and men to make incremental improvements. Furthermore, although no single technological innovation can transform the social hierarchy, it can provide opportunities for females to work for changes that recognize and valorize their vital contributions to their families and communities. The role of the farmers and the community is essential to Bhungroo's sustainability.

Taken together, the introduction of the Bhungroo technology, whereby groups of women jointly own and manage the water recharge and storage system, has created a powerful form of informal water rights that is transforming women's roles in household and community decision-making. Even without formal land titles or legal water rights, these women control when, how, and for whom the stored water is released for irrigation. This control affects crop productivity, seasonal planning, and household income, giving them a tangible and respected say in economic matters traditionally dominated by men. For example, in several women's groups, members have negotiated water allocations among neighboring farms, decided on cropping patterns, and collectively reinvested earnings from surplus yields into better seeds or equipment, decisions that were previously made solely by male relatives. In the local cultural context, such de facto control over a critical resource is often more visible and accepted than distant legal entitlements, because community members witness the women's contribution to agricultural success in real time. Joint Bhungroo ownership has thus elevated their social status, with male farmers acknowledging them as "water managers" and community leaders. In effect, this socially recognized authority functions as a step toward reducing the disparity in property rights, because it is grounded in daily practice, collective benefit, and community trust.

Next, we interpret our findings within the local and global sociopolitical economic context to frame the farmers' interviews within ongoing climate crises. One example in the Bhungroo irrigation innovation is by the cofounder of Naireeta Services, Biplab Paul, who regularly interacted with technicians in the field who were helping him collect soil samples and install the irrigation equipment. Paul noticed that young adolescent boys who had dropped out of school idly hanging around the villages needed to be included in the project. Thus, to help them feel useful and give them a sense of purpose, Naireeta Services readjusted the Bhungroo irrigation program to train the young adolescent boys to collect data on soil salinity and help install the irrigation equipment. At the same time, the other cofounder of Naireeta Services, Trupti Jain, worked on a corollary project to address the rise in violence against rural women, which also had increased as male farmers had become frustrated with not finding gainful employment. Traveling from their home base in the city of Ahmedabad and observing climate change challenges throughout India and in the neighboring countries of Pakistan, Bangladesh, and Afghanistan, Jain and Paul began to see that modest gains toward female empowerment included creating opportunities to engage the whole community.

This study highlights climate technologies and the importance of grounding them in their specific context regarding resource availability, community, job availability, education level, and environmental issues. The low cost of the Bhungroo irrigation technology and its continued benefits to communities have important global implications. Overall, our findings converge with others in underlining how important it is that adaptation strategies fit the local context (Deb and Haque 2017; Khan et al. 2004; Kihila 2018; Shuaibu et al. 2014; Tashmin et al. 2018). Most important, it is important to continue to define how different contexts shape responses to climate change and the extent to which technological innovations benefit communities (Mah et al. 2020). Increasing vulnerability can lead to external policy and institutionally based interventions which can be reactive, lack foresight, or even undermine or weaken communities (Dube and Sekhwela 2007; Hulme 2004; Mirza 2003).

The success of Bhungroo is closely tied to its origins: it was created by individuals who lived in or had direct experience with the local area. We argue that its benefits stem, in part, from this foundation in local innovation and community-driven establishment. Because autonomy and resilience are deeply embedded in specific social and ecological contexts, interventions are more likely to succeed when they address the problems people themselves identify as most pressing. One effective way to understand these layered vulnerabilities—and the capacity of communities to cope and recover—is simply to ask them. In this project, alongside assessing whether Bhungroo improved crop yields, we sought to do exactly that by engaging directly with farmers about their lived experiences.

Although our study is limited in scale and scope, it underscores the need for additional case studies in other regions affected by climate change to examine whether the findings presented here converge or diverge across different contexts. Prior research also highlights how many communities place high value on their own knowledge systems and indigenous practices for adapting to and coping with climate change (Opare, Service 2018). Future research should therefore investigate how the effectiveness of adaptation technologies is shaped by whether they are conceptualized and developed within the same cultural and ecological contexts in which they are implemented.

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Supplemental Material

Supplemental material for this article is available online.

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