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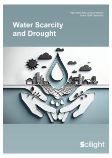

Article

Underlying Dimensions and Determinants of Technological Drought in Relatively Uplifted Regions of Bangladesh

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Abstract: Drought is well known as a natural, stochastic phenomenon, which is characterised by prolonged periods of insufficient precipitation, which can seriously affect agricultural and hydrological processes. Conventionally defined as a slow-acting threat, drought happens over time and can last long since it is the lack of rainfall compared to long-term averages. Drought has four main categories, including meteorological, agricultural, hydrological, and socio-economic droughts, but the traditional definitions tend to overlook the technological aspects, especially in small-scale agricultural systems. In contrast to socioeconomic drought that arises from not being able to meet the water demand, technological drought occurs from the failure of technology and proper management despite getting normal rainfall. The study explores the characteristics and effects of technological drought in the Madhupur Tract of Bangladesh. The study uses fifty-five statements and variables based on a structured questionnaire survey to understand the perceptions of the farmers about technological drought and the factors behind it. The Principal Component Analysis was conducted to reduce the size of the data and determine latent factors that influence technological drought conditions. The analysis indicated ten major components of important dimensions of technological drought and resilience. PC1 lightens technological options to reduce drought effects, PC2 symbolises socioeconomic factors in resilience, and PC3 puts the emphasis on water management and irrigation. PC4 is concerned with energy provision and technological limitations, whereas PC5 is associated with environmental and policy-based issues. PC6 focuses on the importance of cooperation among farmers and the integration of traditional knowledge, PC7 focuses on the problem of access to technologies, and PC8-PC10 focus on the environmental problems and failures in the technical sphere. The findings underscore the need for policies that promote improved water management, enhanced access to appropriate technologies, and the strengthening of drought resilience in smallholder agricultural systems.

Keywords: drought; technological drought; PCA; Madhupur Tract; agriculture; Bangladesh

1. **Introduction**

In everyday usage, the term drought commonly refers to a lack of precipitation, leading to a reduced amount of rainfall available in the ecosystem, and subsequent disruption of agricultural processes. But as the world keeps moving towards an industrial and technology-driven civilization, there is a constantly increasing need to redefine traditional expressions to be consistent with the technological changes. Keeping this in mind, alongside the already existing notions of meteorological, agricultural, hydrological, and socio-economic droughts [1–4], there are other aspects that need to be considered. Because farmers in most parts of the globe are experiencing some form of water scarcity beyond the conventional definition of drought. This additional form of drought has been named 'technological drought' [4]. Unlike droughts caused by lack of rainfall [5], low soil moisture, or low water levels in lakes, rivers and reservoirs, technological drought arises from a failure of water technology and/or a deficiency in land management strategies or practices [4]. To be specific, such drought doesn't occur from the shortage of water in the environment, but because of the inability to access or control it due to constraints in infrastructure, irrigation technology, or socio-economic resources [4].

Technological drought is not patterned like meteorological drought since it may even take place in areas where the precipitation is balanced, yet farmers cannot extract the water using the wells or canals because of technical or financial drawbacks. This drought takes place when an ordinary irrigation pump lies idle during the dry season because of the unavailability or scarcity of diesel fuel or power to operate the pump. During these situations, the drought is not merely a deprivation of rain, but the deficiencies in the structures that were intended to guarantee the supply of water and irrigate the farmland. While meteorological droughts are area-specific and seasonal in nature, technological droughts may range from a brief to a longer time period. They may occur during seasons that are not exceptionally dry, even in flood-free regions [4,6]. Socioeconomic drought occurs when a shortage of water arises from the imbalance between water supply and human demand for water, which restricts people's access to water [7]. However, it may happen following technological drought, as insufficient infrastructure and water management systems may cause the inability to produce sufficient food, and financial pressure on people [4,8]. Technological drought not only endangers their lives, but it also prevents the pace of sustainable development of the region. Technological and/or management failures can severely limit agricultural production in developing countries, despite water resources being available [6,9]. Because the hydrological availability of surface and groundwater resources in rivers, canals, and aquifers does not necessarily ensure their effective application for agricultural irrigation. In practice, farmers often face significant constraints in accessing fuel required for irrigation pump operation. These constraints are further exacerbated by recurrent power supply disruptions and the low efficiency and limited reliability of existing irrigation infrastructure, collectively undermining irrigation performance at the field level. It results in crops and decreased yields [6,10]. Bangladesh experiences technological drought due to the lack of irrigation supplements among the farmers to sustain them during dry seasons, and interruptions of rain during the short monsoon rains.

Many of the studies over the years have examined the physical factors of drought, e.g., rainfall patterns, depletion of groundwater; the technological and institutional aspects have been neglected [11]. These are technological and institutional factors that are taking a central stage among farmers in an environment much like that of Bangladesh, and this applies particularly to the smallholder farmers. Technological drought is not limited to equipment failures since it demonstrates the existing inequality in the community around technology and infrastructure access and their resilience to disruption. The available literature indicates that technological drought is a relatively new study topic, hence the dearth of academic research and data regarding the same. This renders it a new area of study.

Recent research in the South Asian environment indicates that a type of technological drought can exist in otherwise mediocre rainy seasons and is further intensified by institutional inefficiency, poor extension services, and inequitable resource access [12,13]. Also, surface water availability may be further depleted by the upstream dam constructions or other political or transboundary factors, increasing the problems with water management and causing the occurrence of technological drought [14,15].

Bangladesh is a land of fertile fields, and most people are reliant on farming. This has not changed since its establishment; thus, irrigation plays a vital role, particularly for crops, which are in the dry seasons. Despite the government-sponsored projects such as the National Minor Irrigation Development Project (NMIDP) to expand both the irrigation networks, rural farmers are not accessing pumps, fuel, or electricity as they are costly [13]. These constrain the benefits in the event water is present, but these physical constraints of the meteorological droughts can be countered through good management and accessibility of advanced agricultural equipment. This study, therefore, concentrates on the Madhupur Tract, which is a highly drought-prone but agriculturally productive area of central Bangladesh. It examines the perceptions of farmers towards technological drought in this area, and how it is distinct compared to other forms of drought by establishing causes particular to this drought. We used surveys and focus group discussions to collect and analyse data, and used Principal Component Analysis (PCA) to identify critical technological drought dimensions and challenges. In addition, this paper demonstrates how the vulnerability of farmers is predetermined by the inadequate access to energy, reliance on the irrigation system, the inability to afford sophisticated systems, and unfavourable weather. After analysing the issues, in this study, effective drought control strategies in Bangladesh and artificial water-based agricultural lands are generated. The increased significance of technological drought transcends the existing drought management systems. This study contributes to the expanding body of literature that urges the acknowledgement of technological drought as a new type of drought, which requires specific, situational policy and management responses [4]. The paper will have the introduction, section two will contain the data and methods, and the third section will contain the results. The discussion is further expanded in section four, whereas the summary of main findings and conclusions is provided in section five.

2. Data and Methods

2.1. Study Area

The Madhupur Tract region (Figure 1) includes Tangail, Mymensingh, Jamalpur, and Gazipur districts of Bangladesh, which serves as a distinct geomorphological unit separating the Old Brahmaputra and Ganges floodplains and covers 4,244 square kilometers [16]. It is distinct among surrounding floodplains in that it has uplifted topography, whose height ranges between 15 and 30 m above sea level, and has been a part of the Old Brahmaputra and Ganges floodplain boundary. This terrace-like red-brown soil greatly contrasts with the alluvial soil of the lowlands. The soils are characterized by a low level of their fertility and the low level of their ability to retain water, thus forcing farmers to employ irrigation systems and other practices that would allow them to succeed in agricultural practices [17,18]. Physical topography of the area includes Baids and Beels, and depressions regulating agricultural activities, water movement, and seasonal land use patterns. Madhupur tract is located in the sub-tropical monsoon zone and receives 2000–2400 mm of rainfall every year, with 80% of the total rainfall received during June and September. This area has a range of temperatures ranging between 11 °C in winter to 34 °C in summer, with a high relative humidity level throughout the year [19]. The area faces water shortage during pre-monsoon, although it receives heavy rainfall at that time. The low retention capacities of the soils restrict the availability of perennial water supply, and overdependence on electricity and diesel tube wells further adds to the frequent water crises in irrigation. The rabi and early kharif seasons have unpredictable short-run variations in the crop plan and the yield production pattern in the local farming systems. The Madhupur Sal Forest here is among the few remaining parts of the tropical moist deciduous forest in Bangladesh ecologically, despite being seriously devastated due to agricultural land conversion, illegal logging, and uncontrolled residential development several times. Sustainability of resources has also been a problem as vegetation loss has resulted in biodiversity loss, soil erosion, and ecological instability [20]. The Tract of Madhupur has a high population density since there are about 920 people/sq. Km (BBS) [21]. Subsistence farming remains the primary source of income for the local people, which is supplemented by small-scale farming and rural work. The social and cultural environment is also varied, as the local Garo communities also follow their own method of traditional farming and forest-based survival means. The region of the Madhupur Tract is quite delicate, taking into account the extent to which the population density, environmental degradation, climate change, and low land resources affect the stability of the local living conditions.

2.2. Data Sources and Methodology

We used a mixed-methods approach, including both qualitative and quantitative data, for this research. We collected qualitative data through various primary methods, including extensive field surveys, household interviews, and consultations with local agricultural officers, extension workers, and community leaders. We asked them about their perceptions of technological drought, the contextual depth of the farmers lived experiences, and how agricultural practices have changed over the years in the area. Relevant secondary data were also consulted, such as official reports, journal articles, and local administrative statistics. A total number of 471 respondents were interviewed for this research using the Qualtrics online survey form. After data cleaning, error and missing data deduction we get 459. We used these 459 respondents in our study. On ethical grounds, before being interviewed, we read the consent letter and obtained permission to proceed with the interview.

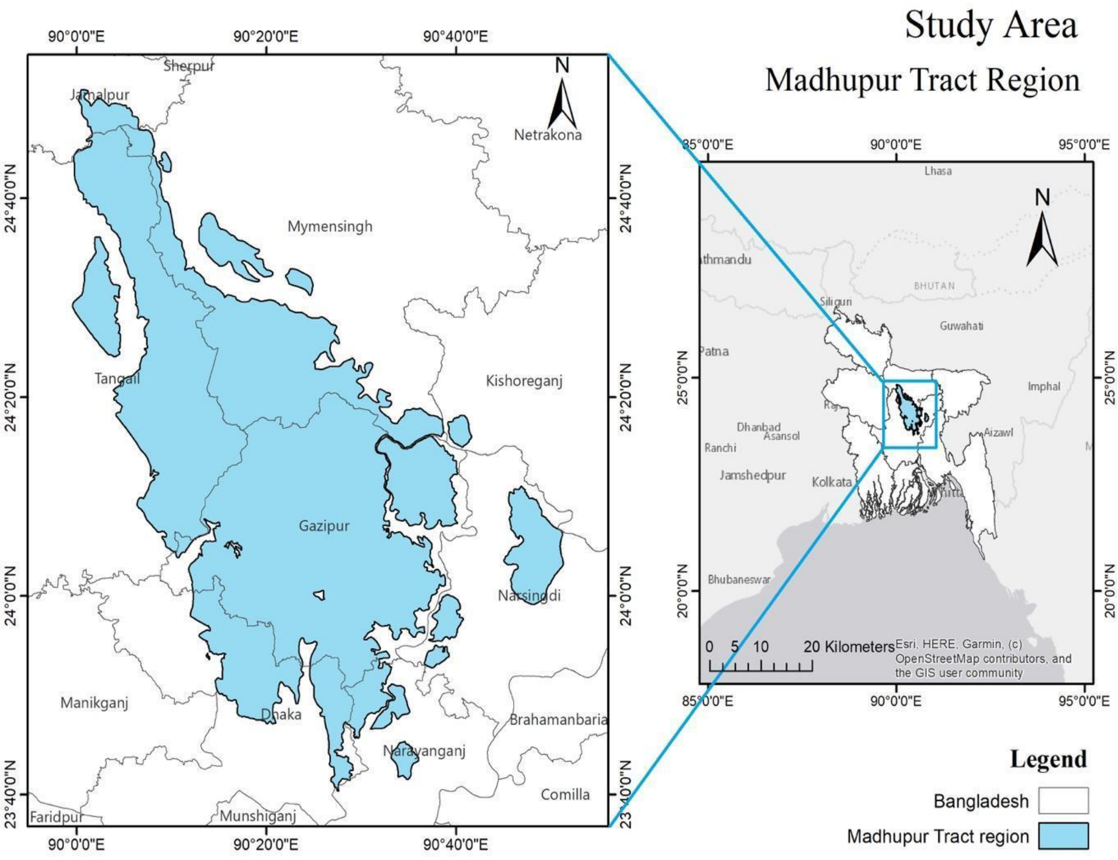

Figure 1. Madhupur Tract Region of Bangladesh.

2.2.1. Stratified Random Sampling Procedure

A stratified random sampling method was used to collect the data from the different socioeconomic groups represented in the Madhupur Tract Region. For this stratified random sampling, first, we selected the upazilas of different districts based on the geographical location of the tract regions. Then, we selected the union of the upazilas and finally selected the respondent randomly based on geographical distribution. Moreover, to get data from a diverse range of respondents, the data was collected from those who are 20 years or older. Most of the respondents (92.4%) were male as most of the farmers are male, due to the low participation of women in the agriculture sector. 7.6% of our respondents were female, who were found working in the field during our survey. In addition, the stratification of farmers and/or those involved in farming was based on their exposure to irrigation, landholding size, education, farming experience, and reliance on rain-based farming, all of which contributed to their susceptibility to technological drought. We collected household lists acquired from Union Parishad offices, agricultural extension units, and community-based organisations, which were used to build the sampling frame. We collected data from diverse respondents from each district across the geographical location. We started a survey in a stratum from one location and moved clockwise, and selected the respondents in each stratum randomly, such that all the farmers would have an equal probability of selection after stratification. This technique substantially improved sampling bias and enhanced the accuracy of statistical inferences, particularly regarding socioeconomic-environmental interactions. This stratified design is in line with the traditional approaches to research on agricultural vulnerability, and causes interpretation of heterogeneity in exposure to drought, behavioural adaptation, and technology adoption to be more effective.

2.2.2. Principal Component Analysis (PCA)

The analysis of the underlying structure among 55 socioeconomic, agronomic, technological, and perception-based variables concerning technological drought of the Madhupur Tract Region was done using Principal Component Analysis (PCA) (Supplementary Materials Box S1). PCA was performed using Pearson correlation coefficients, while the survey items were ordinal and measured on a Likert scale [22,23]. In this research, we used variables with five response categories (Strongly agree to strongly disagree) that are often treated as approximately continuous in empirical social science research. The aim of PCA was to decrease the dimensions and determine latent constructs that characterize the difference in the experiences of drought by farmers, the availability of irrigation, technological constraints, and adaptive ability [24,25].

This approach is widely used and considered reliable and robust under typical conditions, especially when sample sizes are adequate [22,23,26–28]. However, some research identified limitations with this method and proposed polychoric correlation, which we therefore plan to apply in our future research to further enhance the robustness of the findings, given the limitations of the SPSS platform in the current research.

2.2.3. Data Preparation and Screening

Data screening was done at the beginning to determine completeness, distributional aberrations, and multicollinearity. The data set was tested for missing values, discrepancies, and outliers. Listwise deletion was used to address the missing responses in variables with less than five percent of missing values; there was no variable with more than five percent of missing values [29]. The normalization of z-scores was done on all 55 variables before PCA in order to have equal contribution to the correlation structure, as well as having minimum scale-induced bias. Variables with very low communalities (less than 0.20) or redundancy due to the high intercorrelations (r more than 0.90) were reviewed again, but all of them met the validation criterion of inclusion.

2.2.4. Assessment of Suitability for PCA

The Kaiser-Meyer-Olkin (KMO) statistic of sampling adequacy, and the test of sphericity of Bartlett were applied to measure the suitability of the Principal Component Analysis (PCA). For PCA dimension reductions it requires the at least a KMO value of 0.60 for intercorrelation of the variables to extract components [30]. Our KMO Berlet results was 0.94 which indicates the suitability of using PCA to analyse the dimension reduction of the variable while retaining the quality and producing a manageable data size to analyse and model data with many features. The result of the sphericity test was statistically significant ($p < 0.001$) [31], which confirms that the correlation matrix was not an identity matrix, and PCA was suitable [6,32].

2.2.5. Component Extraction

The correlation matrix of 55 standardized variables 55 × 55 was utilized as the input of PCA. Besides, all the elements of the correlation were the coefficients of Pearson correlation between two variables. In order to obtain the eigenvalues (λ_k) and eigen vectors (v_k), eigenvalue decomposition was performed, which is a proportion of the variance that each principal component accounts for [25,33]. Standardization was carried out to ensure that the cumulative variance that was attributed to the correlation matrix equated to that of the number of variables (55).

2.2.6. Determination of Number of Components

Three set criteria were used to determine the number of components that should be retained:

- Kaiser Criterion**:** Elements having eigenvalues of more than 1.0 were kept [34,35].
- Scree Plot Analysis**:** It was observed that the inflection point was at the endpoint of the component eigenvalues, which decreased slowly after the end [36].
- Parallel Analysis**:** Comparisons between observed and randomly generated eigenvalues of the same dimensionality were done to ascertain that each component explained more than the various counts of random eigenvalues [37].

Through these criteria, there were ten main components, which together describe a significant percentage of the entire amount of variation in technological drought indicators [6,38].

2.2.7. Rotation and Interpretation

Varimax orthogonal rotation with Kaiser normalisation was used to improve upon interpretability. The result of this rotation procedure was that it redistributed variance among components and maintained orthogonality and total variance. Rotated loading variables $\geq |0.30|$ were deemed to provide a useful contribution to the component description as per the conventional drought assessment criteria [29,32]. The initial Eigenvalues ≥ 1 was used to determine the number of principal components. We used the Scree plot to show the Eigenvalues and component number of the PCA. We grouped the variables of each principal component based on the factor's loadings. Communalities (h^2) were calculated to know the percentage of the variable's variance that was explained by the remaining components. The identified coherent thematic dimensions were identified using the rotated component matrix, which included water resource constraints, irrigation dependency, perception of early-warning, technological limitation, crop sensitivity, institutional support, and socioeconomic adaptive capacity. Variables that loaded highly on the same component were combined to express the given latent constructs that were applicable to technological drought vulnerability.

2.2.8. Component Scores

Scores on the components were created through the regression method:

$$T = ZV$$

Here, T = the N × K standardized data matrix, Z = the standardized data matrix, and V = the rotated loading matrix. These component scores have since been utilized to decipher the structure of technological drought and also to classify the leading drought-related dimensions in the study area.

All the analyses were done in SPSS under the extraction and Varimax rotation under the PCA module. Scree plot, rotated component visualization, and factor loading visualizations were interpreted. Python was further tested to give stable and reproducible components, and this was done under methodological guidelines developed by Abdi and Williams [24] and Jolliffe and Cadima [25].

3. **Results**

3.1. Basic Characteristics of the Respondents

The results reveal information about the agricultural practices and drought-related knowledge among the respondents (Table 1). We used 459 out of 471 respondent data after data cleaning for this research. The highest number of respondents was seen in the 41–50 age group, which was 30.1%. The lowest number for the age group was 20–30, only 10%. Moreover, 54.9% respondents, which makes up more than half of the respondents, have 4–6 family members. However, their educational qualifications reveal that 25.7% of the respondents had no formal education. From the overview of the distribution of the respondents' occupations, the vast majority of the respondents turn out to be farmers (86.1%). Business holders, service holders, and retirees are, respectively, 3.5%, 1.7%, 0.9%, and the remaining 7.8% are in different categories. Based on the experience of the respondents within the agricultural or farming sector, most of them (26.1%) have around 20–30 years, followed by experience of 10–20 years (23.3%), and lastly, 21.4% have over 30 years of experience. A low percentage of 4.1% indicated no farming experience, and those with 5–10 years of experience comprise 15.9%, and those with less than 5 years of experience is 9.2%. These show that there is a significant difference in the backgrounds of the respondents, their socioeconomic statuses, and experiences. Supplementary Materials Figure S1 shows that April has the highest drought occurrence (81%), followed by May (74.5%), and March (57.3%).

Table 1. Information about the respondents.

(a) Age		
Age group	Frequency	%
20–30	46	10
31–40	74	16.1
41–50	138	30.1
51–60	101	22
60+	100	21.8
(b) Number of family members		
Number	Frequency	%
1–3	71	15.5
4–6	252	54.9
6+	136	29.6
(c) Educational qualification		
Level of education	Frequency	%
Primary school pass	138	30.1
Class 8 pass	108	23.5
SSC pass	44	9.6
HSC pass	23	5
More than HSC	28	6.1
No formal education	118	25.7

Table 1. *Cont.*

(d) Occupation		
Types	Frequency	%
Farmer	395	86.1
Business holder	16	3.5
Service holder	8	1.7
Retired	4	0.9
Others	36	7.8
(e) Farming Experience		
Experience	Frequency	%
<5 Years,	42	9.2
5–10,	73	15.9
10–20 years,	107	23.3
20–30 years,	120	26.1
>30 years	98	21.4
None	19	4.1

3.2. Source of Information on the Weather Forecasts and Status of Irrigation Use

Figure 2a explains the sources that provide the respondents with weather forecasts. Most of them (66.9%) use TV or radio, and 59.9% use self-judgment. The 54.9% of respondents are getting their word of mouth from friends or neighbours, and the 30.3% are getting it from social media, like Facebook. Weather information is supplied to 10.2% of the respondents who get it in newspapers, whereas a small percentage, 4.8% of the respondents, do not get any weather information. This manifests the dominant role of traditional media (radio/TV) along with personal networks in the spread of weather forecasts, which makes significant use of social media and self-evaluation. Figure 2b shows information concerning the use of surface water to irrigate crops amongst 458 respondents. In this case, 64.4% use surface water in irrigation, and 35.6% do not do so. Figure 2c describes the sources of water that were used in cultivation amongst the respondents. The most common is irrigation pumps (52.8%). The second source, with 21.1%, was ponds, and the third source, with 16.9%, was dam water. 5.5% of respondents use artificial reservoirs, and the least prevalent source is wells at 3.8%. This means that the main means of supplying water for cultivation is via irrigation pumps.

3.3. Basic Understanding and Perceptions of the Impacts of Drought

Survey data gives the simple knowledge of the farmers concerning drought and its nature (Table 2), where a high percentage indicated that they experienced drought yearly (62.0%). One sixth of the respondents' experience droughts every 2–3 years, 10.5% and 10.3% experience droughts every five years, and ten years respectively. Other frequencies were indicated by a small percentage, 0.9%. This information shows that the prevalent occurrence among the respondents is the annual droughts. The total period of the droughts (Table 2b) in the Madhupur Tract shows that there were 87 incidences of droughts of 10–15 days (19.0%), 149 incidences of droughts of 15–30 days (32.5%), and 195 incidences of droughts of over a month, but less than three months (42.6%). There were seasonal droughts (3–4 months) 27 times (5.9%).

While noting the variations in the status of drought in the past decades (Table 2c), 56.1% of the respondents claimed that droughts had increased, whereas 19.2% said that there was no change, and 15.9% said that droughts had decreased. Further, one-fourth of the respondents (8.7%) were uncertain about the changes.

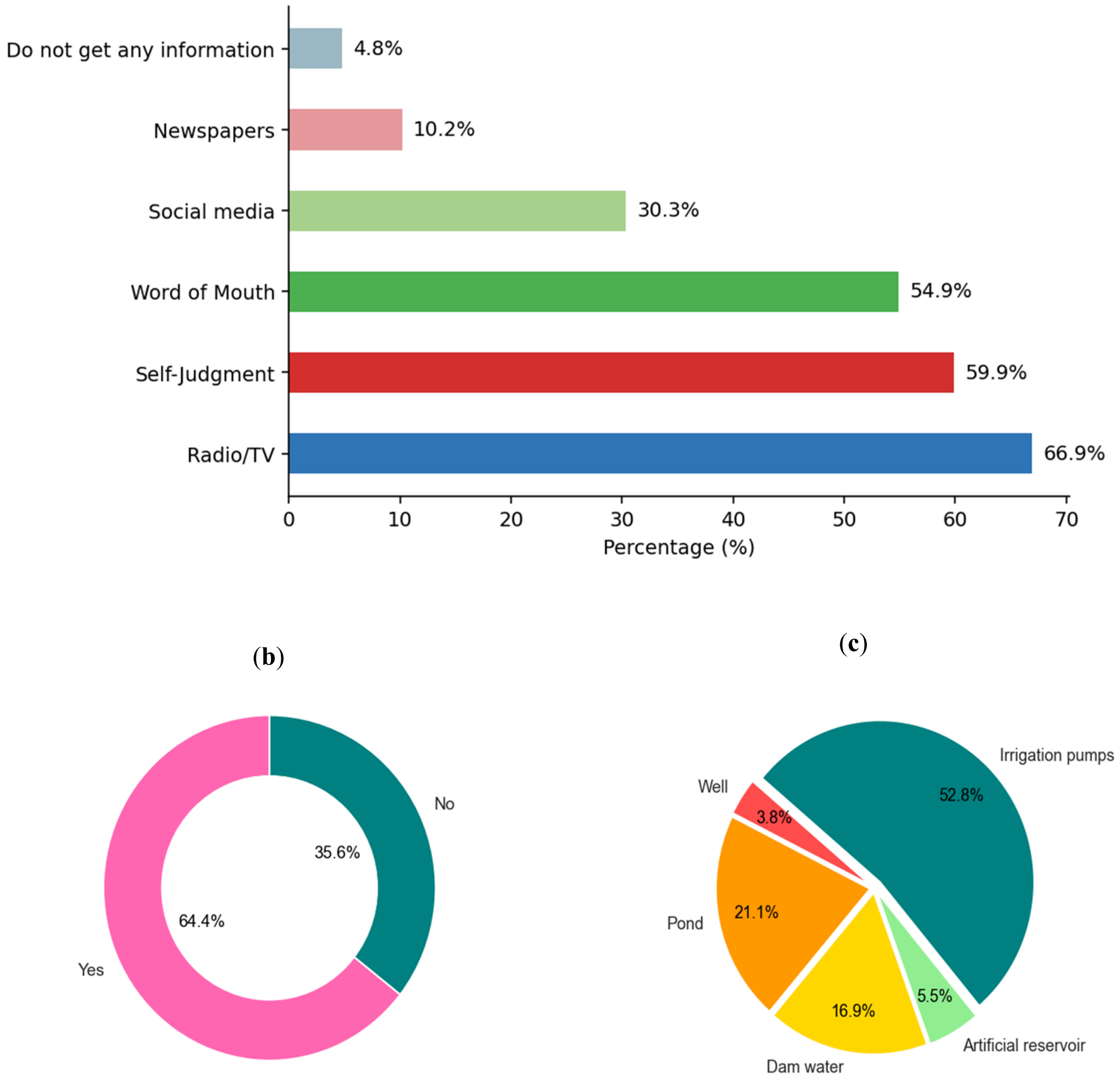
(**a**) (**b**) (**c**)

Figure 2. Source of information on the weather forecasts (**a**), Using surface water for irrigation now (**b**), Source of water for cultivation (**c**).

Table 2. Farmers' basic knowledge and understanding of drought characteristics.

(a) Frequency of drought occurrences		
Drought Occurrence	Frequency	Percent
Every year	284	62.0
2–3 years interval	75	16.4
Once every five years	48	10.5
Once in ten years	47	10.3
Others	4	0.9
(b) Overall duration of drought		
Duration	Frequency	Percent
Very short time (10–15 days)	87	19.0
Short time (15–30 days)	149	32.5
More than one month but less than three Months	195	42.6
Seasonal (3–4 months)	27	5.9

Table 2. *Cont*.

(c) Changing status of the drought in recent decades		
Status	Frequency	%
Increased	257	56.1
No difference	88	19.2
Decreased	73	15.9
Don't know	40	8.7
(d) Frequency of drought 30–40 years back compared to the recent decade		
Status	Frequency	%
Definitely not	25	5.5
Probably not	91	19.9
Might or might not	60	13.1
Probably yes	210	45.9
Definitely yes	72	15.7
(e) Anticipation of the onset of drought forecasting		
Status	Frequency	%
Yes	282	61.6
No	176	38.4

Besides, the comparison of the frequency of droughts (Table 2d) in 30–40 years and in the recent decade, with 210 respondents (45.9%) of the opinion that droughts are likely to go up, and 72 (15.7%) of the opinion that it is definitely going to go up. On the other hand, 91 (19.9%) respondents believe that droughts are unlikely to have increased at all, and 25 (5.5%) are certain that they have not. The other 60 respondents (13.1%) do not know whether the change will happen or not.

The data (Table 2e) shows that among those respondents who believe drought is going to happen, there was a good percentage (61.6%) of them who deemed it practical to predict drought and 38.4% of them did not. The above findings indicate that despite the fact that most of the respondents are aware of the significance and prospects of drought forecasting, but a good number of them are still unaware, hence the need to create more awareness of the forecasting systems, their accuracy, and their communication.

Figure 3a shows the perceived impact level of drought, considering their impact on the company, business, and agriculture. 50.4% of the interviewed population stated that they are moderately effected. On the other hand, 27.1% of them reported low impacts, and 19.7% high impacts. In 2.4 incidents, no significant impact was found, but 0.4 cases showed extreme hardship.

In terms of preparedness, the extent to which the respondents had access to modern irrigation technologies, such as electric and diesel-run deep tube wells, low lift pumps, and better economic conditions, felt prepared to cope with any prospective technological drought situation, while those without these felt unprepared and somewhat at risk. Figure 3b highlights that a large number of the respondents (63.3%) consider themselves moderately prepared. 13.5% of them feel that they are highly prepared, while only 2.0% considered themselves very highly prepared to tackle technological drought. Less prepared respondents consist of 16.8%, with the remaining 4.4% considering themselves as poorly prepared.

Overall, moderate drought effects are the most prevalent, yet the number of respondents who feel that they were moderately equipped to cope with the consequences of the drought remains large, and the problem demonstrates the need to increase preparedness and resilience to the drought aftermath.

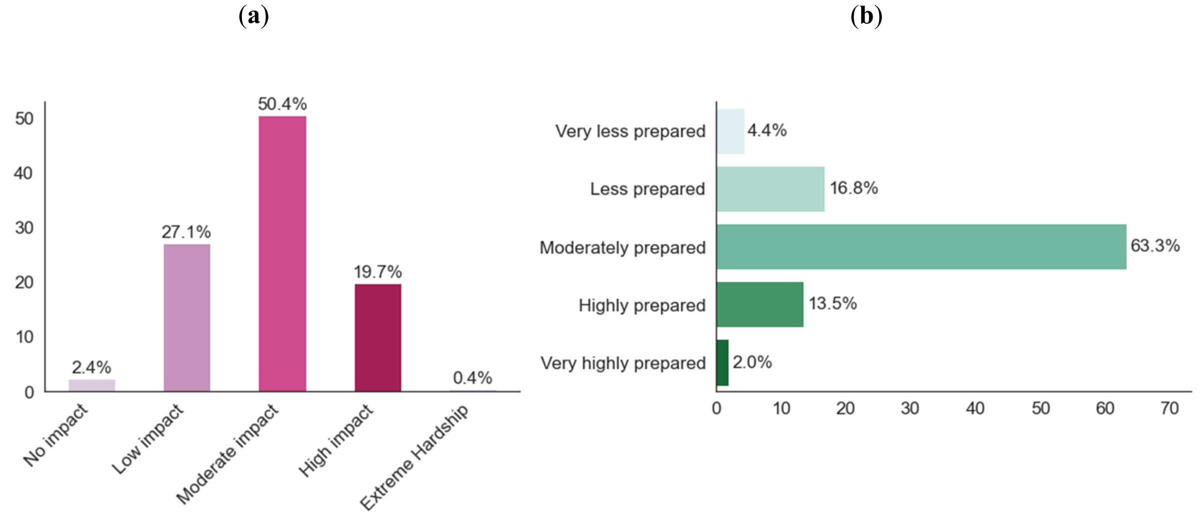

Figure 3. Perception on the impact level of drought over the past decade (**a**), and Preparedness levels for drought (**b**).

3.4. Characteristics of Modern and Traditional Irrigation Methods and Their Usage

Figure 4 demonstrates the usage of modern and traditional irrigation methods by the interviewees. The modern irrigation methods shown in Figure 4a demonstrates groundwater-based technologies to be the most common ones used today. The most popular types of electric systems are shallow tubewell electric (89.08%), deep tubewell electric (82.63%), deep tubewell diesel (78.82%), shallow tubewell diesel (77.73%), and low lift pump diesel (76.20%). On the other hand, drip irrigation (52.62%) and subsurface water lines (60.04%) are not widely used because they are more advanced or hard to reach. In the 'currently not using' category, 'others' is close to 88%, which is a remarkable trend showing high discontinuation or non-applicability of the methods. 'Used before' (around 35–50% for most methods) and 'not used before' (around 42–57%) are significant in the non-use group. This suggests that people stop using something because they have used it before, not because they haven't been exposed to it. "Never used" is still low for most modern systems (less than 15%), except for drip irrigations (27.73%) and others (about 31%). This shows that most people are aware of and have tried modern techniques. Figure 4b shows that the current use of the traditional irrigation methods is much lower in most categories. Only furrow irrigation (56.77%) and terraced irrigation (24.67%) show moderate use. Most traditional methods, like doons (about 14%), rower pumps (5.24%), and treadle pumps (about 6%), are not used very much today [39,40]. On the other hand, "currently not using" is by far the most common answer, often more than 75–90% of the time (e.g., rower pump 94.76%, treadle pump 94.10%). A large percentage of the people who don't use this category (about 40–75%) say they "used before," which means that many traditional methods were once used but are no longer used. At the same time, "not used before" and "never used" together make up a smaller share, but they are still important in methods like BRRI diaphragm pumps and furrow irrigation. In general, the statistics show a shift from old-fashioned to modern irrigation. Traditional systems are becoming less useful, mostly because they are being replaced rather than because people don't know how to use them.

3.5. Statement and Variables of Technological Drought

To examine the perception and behaviour of farmers on technological drought, a total of 55 variables were developed (Supplementary Materials Box S1) and included as a methodology in the survey in the study area. These are some of the statements that contain numerous factors that shape adaptation. These are irrigation facilities, availability of energy, social and economic background, environmental constraints, and the application of technology in drought management. The identified statements were grouped further using Principal Component Analysis, which was used in order to minimise redundancies and allow identification of patterns as well.

Ten PCAs were examined, and each of the individual statements is classified under one of the PCAs (Supplementary Materials Table S1). The statements about things like irrigation availability and ownership systems- investigate the questions about the availability of the water, fragmentation of the land, and governance of irrigation. Moreover, statements of energy and fuel will give the required information on the potential restrictions of infrastructure, including load shedding and diesel prices, which can intensify the drought effect on farmers. Socioeconomic variables that include household income, education, and institutional access are also discussed in the statements and affect drought response. It is also evident in the statements that transboundary water politics and environmental problems influence the water resources by constructing dams and extracting water upstream. The statements show the meetings between agricultural technology development and the challenges of operation, which are caused by inaccurate weather forecasting, which delays irrigation systems. The final group of statements provides the perspective of farmers regarding drought resilience, the way they are assisted by policy, and their embrace of new technologies, which are the social and institutional framework of drought resilience. The 55 statements are able to equip the researchers with the necessary information to analyse and capture the multifaceted nature of technological drought that is afflicting the agricultural sector in Bangladesh.

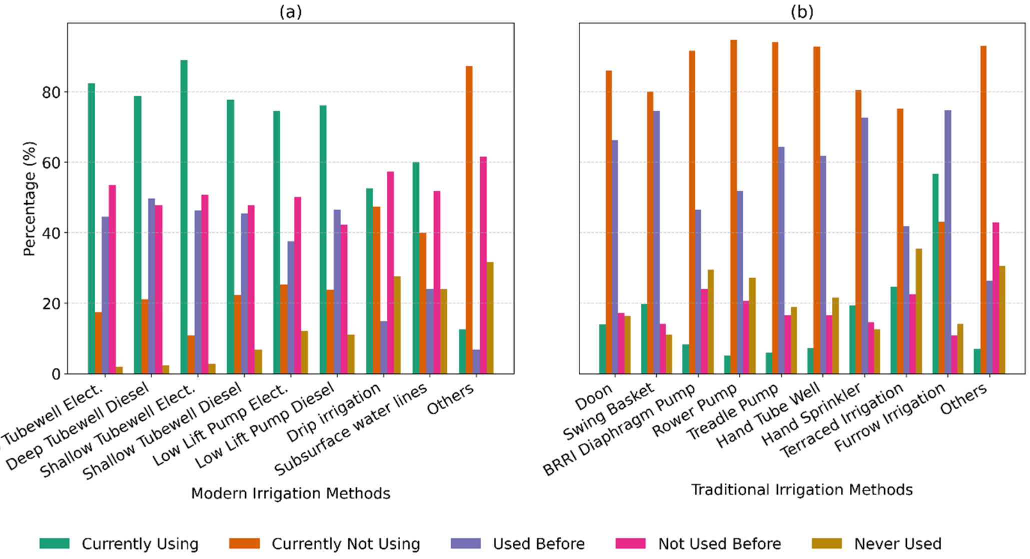

Figure 4. Use of Modern (**a**) and Traditional (**b**) Irrigation Methods for Cultivation Purposes.

3.6. PCA Diagnostics, Components and Variances of Technological Drought

Our KMO Berlet score was 0.94, indicating the suitability of using PCA for dimension reduction of the variables while retaining quality and producing manageable data sizes for analysis and modelling with many features. Ten principal components were identified that explained a squared rotation sum of loading 61.93% (Figure 5; Supplementary Materials Table S2). This indicates that the dataset is distributed across dimensions rather than concentrated in a few dominant components. The fragmented nature of component loading suggests that there might be some other components that are responsible for the occurrence of technological drought in this region, that we might not have taken into consideration.

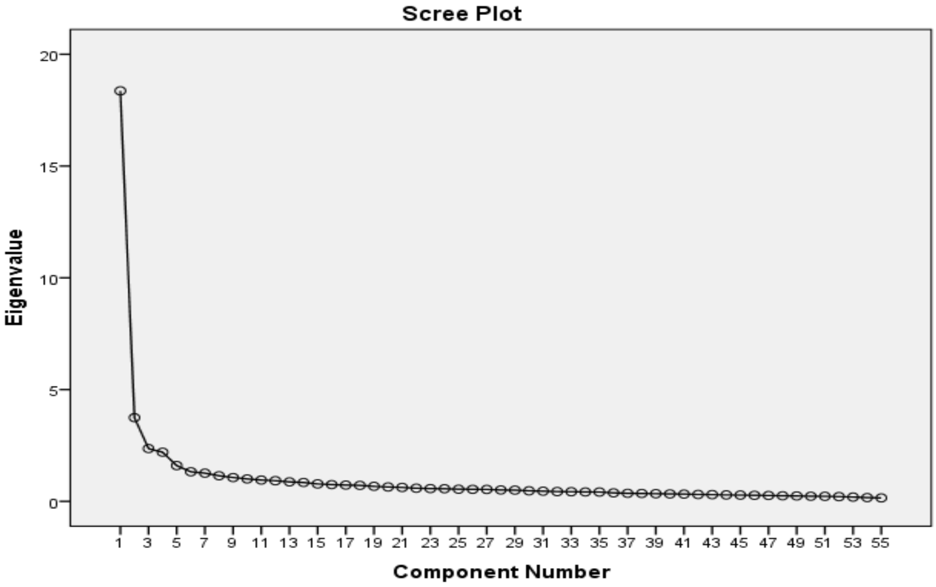

Figure 5. Scree plot of PCA.

In a further effort to visualize the elements, the Rotated Component Matrix obtained by the Principal Component Analysis (PCA) using the Varimax rotation was presented in the form of a clustered heatmap (Figure 6). The heatmap represents a variable in each row and one of the ten components in each column. The intensity of the color shows the strength of the correlation (or loading) between each variable and component. The variables that have increased loadings (near either 1 or −1) have a stronger association with a specific component. An example is the variable, investing in research and development of new technological solutions to match drought problems in agriculture, which has a high loading (0.72) on Component 2, which means that it is strongly related to the components. A subsequent analysis of the ten items based on these findings allows one to interpret the ten components as different underlying dimensions of technological drought perception.

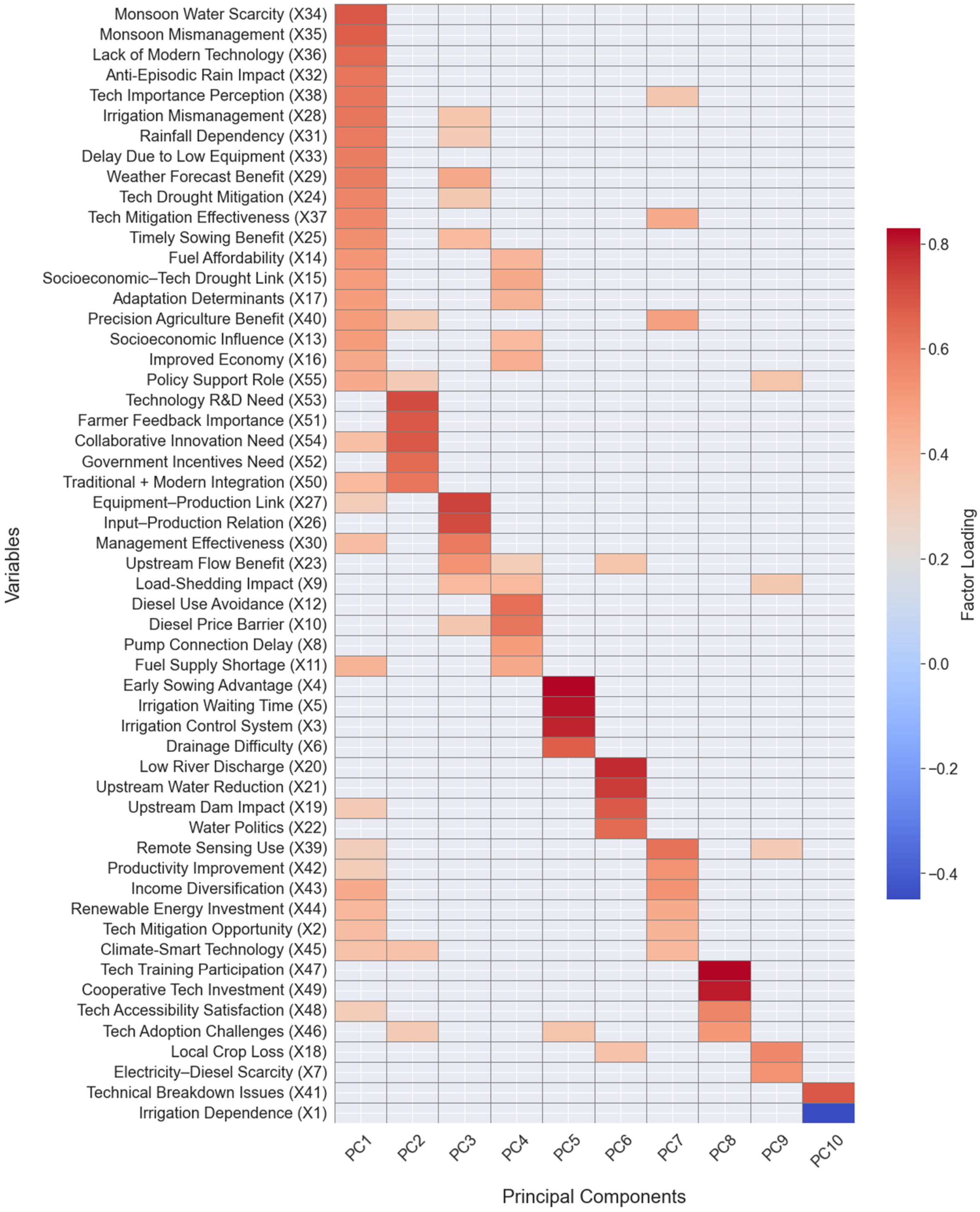

Figure 6. Clustered heatmap of the Rotated Component Matrix of the Principal Components of limitation and underlying dimensions of technological drought perception.

3.7. Underlying Dimensions and Limitations of Drought Management

3.7.1. Water Management and Technology Deficiency (PC1)

PCA1 includes 19 out of 55 variables, and it explains 15.598% of total variance. This component emphasizes the significance of technology when addressing the problem of drought and the barriers that farmers must overcome to access it. In addition, it includes the critical importance of modern technology in terms of maximizing the use of water and irrigation during drought periods. Modern irrigation systems, such as drip irrigation or sprinkler technology, can help farmers to irrigate their land on time during drought, thereby keeping them on track with their crop season. Without this technology, farmers cannot sow on time, which in turn affects their yield and income, keeping them in poor socioeconomic conditions. This results in a drought situation caused by a lack of water management and the lack of use of modern irrigation techniques during the drought season, and more so in the monsoon season. Other elements in this element involve the use of technologies that are precise in agriculture, the use of feedback from farmers in the design of technology, and government subsidies on technological solutions. The socioeconomic issues, namely, credit shortage, inefficient extension facilities, and insufficient government support, reduce the ability of the farmers to utilize the tools. This gap can be filled by including the perspective of the farmers when developing the technology and helping in the policy formulation. Also, proper and efficient water management, availability of technology, and government-sponsored programs are necessary in order to maximize the use of water, which is a valuable asset. It also assists farmers to be more resilient to the effects of drought and plant at the right time to produce the maximum amount.

3.7.2. Policy and Collaboration (PC2)

PCA2 includes 5 out of 55 variables, and it explains 7.348% of total variance. This aspect concerns the socio-economic forces that drive farmers to acquire drought resilience using technology. It indicates that the degree of technological drought is positively related to the socio-economic factors. It demonstrates that the income, education, and access to credit of a farmer help in adaptation to drought conditions. The worse the socio-economic status of a farmer is, the harder they are affected by technological drought. In the promotion of resilience, it also brings out the role played by policy support, research, and collaboration. Farmers are prone to investing in long-term adaptation strategies and embracing modern farming practices where there is a robust network and support systems.

3.7.3. Agricultural Inputs and Production (PC3)

PCA3 includes 5 out of 55 variables, and it explains 6.599% of total variance. The system demonstrates that the supply of water on time and proper supply of farming resources, when used in conjunction with proper management systems, can improve crop yield. The irrigation systems are severely affected and consequently hamper the production process in case irrigation systems are delayed and there is a lack of essential imports during drought. But nowadays, farming tools and adequate field management assist farmers in addressing the issue of water stress. For mitigating sustainable agricultural practices and technological drought, there is a need to ensure upstream water flow, especially when there is a drought, and to reduce the incidence of load shedding. The statements show that the water scarcity slows down the sowing by slowing the yield, simultaneously demonstrating the power of effective management practices and upstream water flow that can result in increased yields.

3.7.4. Fuel, Energy Supply, and Controlling the Irrigation System (PC4)

PCA4 includes 4 out of 55 variables, and it explains 5.927% of total variance. This component shows that the negative impact of energy scarcity, e.g., regular load-shedding or excessive diesel prices, may prevent timely irrigation. In addition, the malfunctioning drought surveillance technology presents an enormous impediment to drought control.

3.7.5. River and Upstream Issues (PC5)

PCA5 includes 4 out of 55 variables, and it explains 5.602% of total variance. This element underlines the importance of environmental and transboundary issues in the availability of water, thus causing drought. Farmers said that the alteration in river flow, decreased discharge, and dam operations upstream had serious effects on local irrigation. The lack of upstream cooperation among the countries involved in sharing water and political problems between nations also contributes to the situation. Therefore, on top of natural drought conditions, it is intensified through human interventions, which can be prevented through fair policy implementation. This can be reduced very well by proper operation of the dams and equal distribution of water in the dry period.

3.7.6. Technological Adoption, Collaboration and Outcomes (PC6)

PCA6 includes 4 out of 55 variables, and it explains 5.567% of total variance. This element is about the collaboration between farmers and collective efforts. When farmers work collectively as a community, they can tackle the drought situation better. If they are able to share knowledge, tools, and infrastructure, there will be a possibility to invest in such solutions as solar pumps or the development of a better irrigation system. It is demonstrated that it can significantly lessen the stress of farmers who need to timely plant their crops through farmer-specific cooperatives, training, and resource sharing. The individual farmer may find it hard and costly to invest in drought-adaptation technology, but jointly sharing this cost will ease the burden on an individual and also enable many other people to combat the effects of drought.

3.7.7. Integration of Traditional Knowledge and Modern Technology (PC7)

PCA7 includes 6 out of 55 variables, and it explains 5.145% of total variance. This component shows that bridging the rift between conventional farming and the new technological approaches can enable farmers to be resistant to droughts. Moreover, the traditional agricultural methods of earlier generations are still prevalent among the rural Bangladeshi farmers, and the Madhupur Tract region is no exception. Such conventional agricultural methods are in line with the Sustainable Development Agenda. A combination of the traditional farming methods and the new technology gives better crop yields and greater resistance to droughts. When farmers are able to share knowledge, tools, and infrastructure, there will be a possibility to invest in such solutions as solar pumps or the development of a better irrigation system.

3.7.8. Challenges in Accessing Technology (PC8)

PCA8 includes 4 out of 55 variables, and it explains 4.994% of total variance. This element brings out the hindrances that prevent farmers from accessing and using modern technology systems. The key issues are machine failures, insufficient training, excessive complexity of the tools, or their inability to fit local requirements. Their tools are not common due to their untrustworthiness, and the prices are so high that the farmers cannot afford them. The farmers in the study area established that the modern tools, such as the mobile weather forecasting, irrigation pumps, and drip systems, have potential. However, they are difficult to use as they are complex in operation systems, have not been tailored to the local contexts, and also demand specific technical skills that are not available to the farmers. Thus, technological availability and required operating training should be carried out at the same time.

3.7.9. Negative Environmental Impacts of Drought Management (PC9)

PCA9 includes 2 out of 55 variables, and it explains 2.820% of total variance. This element illuminates the unplanned effects of economic impacts on the environment, which is brought on by technology without appropriate ecological evaluation. It is through the component that we see how, despite the fact that irrigation systems reduce the effects of droughts, overreliance on technology leads to adverse effects. Moreover, farmers also described that the reliance on natural patterns of rainfall has been reduced since they are able to use electric and diesel-powered pumps to irrigate their farms. High-yield hybrids have led to short-term productivity benefits in the agricultural sector, but have led to the loss of localized varieties of crops that would otherwise have flourished in the natural rainfall and soil environment. These are new crops that require more water, fertilizers, and constant irrigation. The new systems are replacing traditional or local varieties of crop species because these systems place emphasis on high-yielding varieties.

3.7.10. Challenges Due to Insufficient Maintenance and Operational Limitations of Machines (PC10)

PCA10 includes 2 out of 55 variables, and it explains 2.325% of total variance. The last element deals with concerns about the durability of drought management machines and their servicing. The agricultural equipment, like pumps, sensors, and monitoring devices, fails at the time when farmers need them the most. The reason why the system fails is due to a lack of maintenance and late repair services. It is worth noting that in cases where farmers possess farming equipment, their incompetence is evident in not being able to work effectively when they break down, and also a lack of technical expertise at inopportune moments when farming is on the verge. The extreme losses of crop yields also occur due to the loss of irrigation systems during critical periods of crop growth because of the unavailability of alternative water resources and irrigation farming. This dimension describes the problems of equipment spending, training requirements, and infrastructure development. This is because there are regular breakdowns of equipment due to the unavailability of spare parts, repair experts, and local service centers.

The key role of technological drought solutions is rendered useless since such technical systems are not resilient in times when the maximum drought threat occurs.

4. Discussion

The findings of this research offer the background to the critical need for adopting newer technologies to manage the drought-related agricultural risks. The research results demonstrate that drought management difficulties don’t arise from the occurrence of drought, but the restricted ability to manage drought through available technology and infrastructure. The literature shows that in many developing countries, farmers face difficulties in water supply because they cannot access essential data, infrastructure, and modern farming equipment. Many Sub-Saharan African countries, which are heavily dependent on precipitation for agricultural production, have minimal technological assistance, therefore, they are susceptible to technological drought [41,42]. One such instance is northern Ghana, where rural farmer communities deal with water shortage due to poor road networks, low agricultural productivity and poverty [43]. The technological deficiencies should be studied because they help define drought risk that arise from lack of technologies and management.

Globally, many drought-prone areas have available physical water and only lack technology, information, management, and institutional facilities. Droughts caused by these reasons are considered as technological drought [4]. WMO and UNCCD experts identified barriers and technological shortcomings related to drought, including data network and sharing, early warning, monitoring and forecasting system, integrated climate monitoring, impact assessment and delivery systems [44–46]. Integrating and analyzing these data from different sources, including proper management and making them readily available to the science community and the public, are challenging [47–49]. Studies conducted in other regions noted that the resilience of farmers and the availability and efficient application of modern technologies in agriculture are inextricably linked to one another [50]. Previous studies also stated that better irrigation technologies, drought-tolerant crop types, and mechanization can be used to increase productivity when droughts occur [51]. However, many countries lack their own system, and farmers are not well educated to apply it. A significant part of Southeast and South Asia and Africa is beyond electricity connections, while modern technology-based irrigation facilities are scarce in agriculture sector [52].

From our PCA results, it is evident that technological drought in the Madhupur Tract region is not due to the uncertainty of rainfall, but to a combination of technological, socioeconomic, and infrastructural factors, particularly inappropriate irrigation patterns and water mismanagement. The main reasons, as cited by the participants of the survey, behind them not being able to access water to irrigate their lands at the appropriate time were the malfunctioned and old pumps, deteriorated pipes, and lack of modern irrigation systems. Unlike Lobell et al. [53], who have attributed the crop yield variability solely to the climatic factors such as rainfall and temperature changes, our findings show that irrigation and input management have a strong influence on crop yield. The water supply could not be guaranteed because the irrigation systems do not work during the short dry seasons or late rains. This consequently resulted in stress on crops, which effectively has an effect on yield. Mondol et al. [4] also established that the effects of drought are experienced even when there is adequate rainfall, in case the irrigation systems and water management systems fail to meet standards. In addition to meteorological causes, infrastructural and institutional vulnerability also has an equal effect on contemporary drought-related impacts [54].

Shahid and Hazarika [55] stated that groundwater irrigation is important in improving agricultural productivity in Bangladesh. They also mentioned this as the main adaptation measure. Contrary to that, our results suggest that modern technological advancements are not always enough to guarantee drought resilience because they are heavily constrained by energy deficits and financial limitations of the farmers. The operational limitations of relevant machines due to insufficient maintenance are another problem that arises. Similar complications of diesel pump failure and ineffective modern irrigation methods were also reported in the case of Bangladesh, as cited by Luo and Rahman [56]. One of the limiting factors to irrigation has always been limited energy access. According to the farmers, there are frequent power outages, scarcity of diesel, and high costs of running irrigation equipment. A report by the World Bank [57] stated that the irrigation sector in Bangladesh depends on 1.6 million diesel pumps. In order to run these, it will need around 1 million tonnes of fuel each year. The same report also mentioned that frequent power outages, high energy costs, and malfunctioning equipment are the major limitations to the capacity of irrigation, which was reported by the respondents of the survey. The uncertainty surrounding the availability of energy is also another issue that the farmers emphasized, claiming that their ability to irrigate their farms is directly affected by it. Mondol et al. [4] reported that unreliable energy supply and fuel shortages are the primary reasons for technological drought in Bangladesh.

Our results indicate that the level of technological utilization and resilience is influenced by socioeconomic inequalities. The educated farmers who were financially stable and had access to credit could afford fuel, keep pumps operating, and take part in government programs at times when resources were scarce and found themselves at a disadvantaged position. Socioeconomic status was also established as one of the major determinants of vulnerability by Mondol et al. [4]. Moreover, Kanti [58] stated that the 1994 drought harmed poor households throughout Bangladesh, while other studies showed that in northern Bangladesh, low-income farmers suffered the most from drought due to weaker recovery capabilities [15,59–61]. In line with this, research studies in agricultural development show that having financial capital, a larger size, and access to credit are correlated with technological adoption and resilience [51].

Access to technology does not equate to positive technological adoption outcomes. The access should also be combined with the proper information sharing and training of farmers. As has been mentioned in the course of the previous research, inefficient information sharing and transfer of technical knowledge might restrain the effects of agricultural innovations [50,61–63]. These results highlight the significance of providing a considerable amount of institutional assistance that would allow farmers to be aware of the working principles of new technologies and be able to access them.

Community organization and knowledge-sharing practices are considered to be the key to drought management. Our PCA elements point out that cooperative irrigation, groups of farmers, and mutual training programs assist in minimizing vulnerability. Also, Habiba and Shaw [64–66] showed that disaster risk management programs in community scales helps farmers in rural areas to adapt as a community instead of individuals, as this helps in achieving the spirit of community. Similarly, De Graaff et al. [67] reported that the participatory approach of water management led to high-quality adaptation in drought-prone regions where farmers were not given the necessary resources adequately. Therefore, specific social groups and organizations that can be effective towards winning the technological drought are those that focus on the farmers, in the form of better access to irrigation technology and knowledge. Both the institutional and policy structures affected the results. Our results suggest that water diversion and the construction of dams are also done upstream, leaving less water to be used by farmers in irrigation. Ahmed et al. [68] observed that, when dry seasons were experienced, the amount of water that flowed in Bangladesh due to Teesta River diversions was significantly reduced. Also, Arfanuzzaman [69] concluded that water sharing in the basins of the Ganges, Brahmaputra, and Meghna increased the risk of downstream agriculture.

Chan et al. [54] also confirmed these findings, saying that institutional structures and policies have been significant causes of the impact of droughts. There were also reports by the farmers that subsidies, credit schemes, and extension services directly affected their adoption and subsequent maintenance of said irrigation technologies [70]. It was also stated that the use of technology has positive impacts on families and society as a whole. Better production of farmers resulted in increased household food security, which also contributed to keeping the market stable and reducing the trend of migration. Equally, previous studies suggest that widespread adaptation strategies yield regional-level advantages, which increase the capacity of the affected communities to withstand environmental shocks [51]. It was also stated that the use of technology has positive impacts on families and society as a whole.

In this study, the evidence gathered points to technological drought in the Madhupur Tract being the aggregate outcomes of lack of adequate water systems, untrustworthy energy supply, community and socio-economic inequalities, and community organizational structures and policy models. These results highlight findings illustrated in research studies in South Asia, that drought susceptibility needs consideration of the socio-technical systems that regulate the access to irrigation and rainfall patterns [4,68,69].

5. Findings and Conclusions

Our findings suggest that drought occurrences have escalated in the Madhupur Tract region. While the duration of drought occurrences is short, April and May are considered the most affected months. It is perceived that agriculture and business are moderately affected by the drought, but a large number of the interviewed population aren't prepared to cope with it. Farmers used to follow traditional irrigation methods before, however, a large number of them now use modern irrigation systems, including deep and shallow tube well (operated by electricity and diesel), while a few still use the traditional methods. We found ten underlying challenges regarding technological drought, associated with the deficiency of irrigation technologies and energy supply, delay in proper water supply, and people's socioeconomic conditions. The socioeconomic restraints, such as poor education, minimal access to modern infrastructure and energy sources due to poor economic condition hinder the technological drought management to a great extent. Thus, despite using several modern irrigation methods, a gap exists between water demand and supply in the region. Also, lack of community-based cooperation and inefficient knowledge-sharing programs restrain the productivity of the drought-minimizing technologies, including drought monitoring, forecasting, and proper water management. This study can help identify the scope for improving water management practices used by farmers and compare the actual challenges faced in the field with the water demand to address the problem of technological drought in the region. Our findings are relevant in South and Southeast Asia, Africa and similar regions elsewhere, which face similar challenges.

Policies should focus on regulating proper power and water supply, modernizing the irrigation technologies and ensuring their accessibility to the local farmers. However, water resources should be allocated to reach farmers who lack modern irrigation technologies first, as they are unprepared to withstand technological drought.

Rigorous awareness and training programs should be conducted to educate the farmers about the various aspects of technological drought and the ways they can overcome the consequences of them. These initiatives will enable farmers to develop understanding of irrigation technologies, while learning about adaptive methods, ensuring a sustainable balance between agricultural water needs and available water resources. Furthermore, the research needs to broaden its boundaries by using extensive geographical and time-based datasets which include detailed climate models and extended economic development patterns to study the technological drought phenomena.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2605111507232850/WSD-26020018-SI.pdf.

Author Contributions

M.A.H.M.: Conceptualization, methodology, writing first draft, software, validation, analysis, review and editing; H.R.L.: Software, visualizations, analysis, writing draft, editing; S.A.: Software, visualization, editing; R.A.M.: Analysis, editing; H.R.: Review, editing; X.Z.: Review, editing and D.D.: Review, editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The department of Geography and Environment of Jahangirnagar University provided the ethical review and approval needed for the study.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The datasets used and/or analysed during the current study available from the corresponding author on reason able request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Grammarly to ensure the grammatical accuracy of certain sentences. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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