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Agricultural Vulnerability to Climate Change: A Critical Review of Evolving Assessment Approaches

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Abstract

The cumulative negative effects of climate change make agriculture increasingly vulnerable, with severe food security challenges, especially for developing nations. A robust research approach and a logical methodical framework can holistically assess the occurrence and intensity of agricultural vulnerability in a bid to strategize mitigation measures. This paper includes an in-depth review of the existing body of literature on agricultural risk and vulnerability, apart from recent studies and metric measurements of vulnerability having an emphasis on agriculture. Unlike the high priority on climate indicators in the past, contemporary research is progressively comprehensive and multidisciplinary where socioeconomic factors are integrated to make the assessment all-encompassing. Though this review paper found six major types of methodologies, the current vulnerability studies are predominantly index-based experiments adapted from the IPCC vulnerability concept. However, there is considerable variation across experiments concerning vulnerability conceptualization, selection of indicators, weight assignment and indexing techniques. Majority of the indexes encapsulate expert-recommended variables under sensitivity, exposure, and adaptive capacity. Such index-based measurements describe and compare vulnerability over space and time in order to formulate actionable policy measures. Uniform and robust techniques in indicator selection and statistically tenable weight allocation should be pursued in future research. To make the index highly representative and validated, the inadequacy of community perception should be minimized through the integration of PRA techniques within the experimental framework. Emerging threats such as loss of labour productivity in agriculture should be included in the analysis. The components of vulnerability also need to be analysed to comprehend their individual share in overall vulnerability for well-targeted mitigation measures. Constraints of data insufficiency required for vulnerability studies need attention for quality vulnerability research in the future. With such set priorities and focus, future research outcomes in vulnerability evaluation should be more meaningful and policy-focused.

Keywords

Vulnerability; Sensitivity; Adaptive capacity; Labour productivity; Climate

Introduction

The impact of climate change is the leading global threat endangering the existence and development of humanity. The increasing occurrence of climate extremes in the last five decades has shaken the civil conscience and awakened man for climate-appropriate actions across the globe. The pervasive nature of climate change effects has impacted every sector. At the Earth's surface, successive decades in the last 50 years have been felt noticeably warmer than preceding decades (IPCC2, 2013). The scale, intensity, and projected harms, in the long run, have united various countries, researchers, practitioners, and policy makers for deep deliberation to formulate and implement actionable measures to reduce vulnerability. Climate change has far-reaching and complex bearings on biophysical and socioeconomic systems; however, its specific impact on agriculture is enormous and multifaceted since food security remains a concern for several low and medium income countries like India. Agriculture production is severely impacted by climate extremes (IPCC1, 2001). The resultant adverse consequences will be far more severe and frequent in the coming years making the planet more climate-vulnerable (Pattnaik and Naryanan, 2009). The regions that fail to adopt adequate and effective adaptation measures will bear the brunt of food insecurity (Lobell *et al*., 2008). The large population, geo-spatial location, and bio-physical diversity make India one of the most vulnerable countries in the world (Sakhare, 2019). The high incidence of flood, submergence, drought, and saltwater intrusion in coastal areas will impact the overall welfare of the nation with an estimated 3 million persons facing coastal flooding (IPCC4, 2022). Vulnerability analysis is a dominant analytical tool that describes susceptibility to potential risks and remedial actions for risk reduction (Adger, 2006). The global research on climate change and associated vulnerability are, therefore, now more institutionalized, integrated and evolving at a faster pace with the engagement of a multidisciplinary team of academicians and experts. Significant research progress until now has been made to comprehend the nature, magnitude, and interplay of different dimensions of vulnerability to climate shocks. Climate vulnerability research accelerated in 1988 with the creation of the Intergovernmental Panel on Climate change (IPCC) by the World Meteorological Organization (WMO) and the United Nation Environment Programme (UNEP). Since then, IPCC with its scientific findings derived from contemporary research is positively influencing governments for climate-smart policy and helping them with several climate change negotiations. The growing body of knowledge in this field is highly concentrated on assessing the current overall vulnerability status of a region, and to alert stakeholders about the potential adversities. IPCC periodically evaluates and releases the risk and vulnerability assessment frameworks, which are largely employed by researchers to carry out climate studies. These experiments usually follow quantitative methods to produce index-based measurements making them comprehensive and comparable.

The evolving trend and focus of climate change research increasingly recognize agricultural vulnerability as a distinct research theme requiring a well-conceptualized research focus. There exists a dearth of studies globally that exclusively explore and enrich the scientific basis and knowledge to capture how agriculture is vulnerable to different climate events. The study of agriculture vulnerability needs more intensive investigation on account of its direct and linear linkages between agriculture production and climate parameters. The large spatial variation in agricultural outcomes due to differences in biophysical and socioeconomic factors further stresses the importance of research efforts in this domain.

The challenge of feeding over 10 billion people by 2050 (UN, 2015) in the face of the negative effects of climate events is enormous. With the ever-shrinking resources, like land, and dominance of a large number of poor and small scale farmers in developing countries, like India, this challenge is even more complex. Therefore, it is a call for concern for an in-depth research approach quantifying agricultural vulnerability with greater precision. The present review study emphasized a structured reflection of past thematic works, current practices, and recommendations for future research. In addition, this study intends to help the scientific community, especially researchers, organize their research approaches for quality outcomes. This paper has intensively reviewed and presented an updated status of research direction on some major components — risk analysis and vulnerability measurement approaches, the evolving concept of vulnerability to climate change, the analytical framework of and recent research on agricultural vulnerability to climate change effect, currently used measurement techniques for agricultural vulnerability, research gaps, and priorities. Emphasis is, however, laid on evolving concepts, approaches, and metric measurement of agricultural vulnerability.

Methodology

A review of available literature without any pre-set publication date criteria was the methodology adopted for composing this paper. The paper extensively reviewed the status of vulnerability, especially agricultural vulnerability, generalized the research trend, inferred new knowledge, and identified research gaps and constraints to foster innovation in future research. The peer-reviewed literature carries relevant terms or combinations of terms, such as “vulnerability analysis methods”, “climate change”, “climate vulnerability”, “agriculture vulnerability”, “sensitivity”, “exposure”, “adaptive capacity”, “GIS and vulnerability analysis”, “IPCC vulnerability analysis”, “indexation methods”, etc. were searched from online sources like Scopus, PubMed, Google Scholar, Web of Science and Copernicus. A total of 1,174 papers were extracted from various electronic searches. Subsequently, duplicated articles were excluded and 64 distinctly relevant articles were shortlisted and categorized based on their exclusivity. The adequate representation of literature on aforesaid review topics was ensured for extensive coverage and interpretation.

The authors used the standard practice of full-text reading followed by backward and forward snowball techniques to avoid the exclusion of any important article. The selected articles were published in different journals and produced from disciplines like agricultural economics, environmental economics, climate research, applied geology, environmental sciences, marine and coastal research, geospatial studies, ecological indicators, humanities and social sciences, natural resource management, and development studies.

Results

Risk Analysis

Risk analysis is the basis for assessing a system's vulnerability to climate change. The connotation of risk varies across disciplines, though in climate science it is "the potential loss of life, injury, or damage of a system, society or community arising out of a hazard (UNDRR, 2015). Risk is also defined as a combination of the probability of a disaster event and its negative consequences (UNISDR, 2009). Sometimes, the losses caused on account of climate risk are difficult to quantify. In disaster management discourse, the risk is often described as a function of hazard, vulnerability, and coping capacity where the hazard is understood as a disastrous phenomenon, a condition that may cause loss of life and livelihoods, social and economic disruption, or environmental damage.

According to IPCC, the concept of risk and working definition has evolved since its first assessment report (AR) in 1990. In its 6th AR (2022), IPCC has postulated risk as "the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems". The 5th AR of IPCC released in 2014 has recognized risk as the intersection of hazard, vulnerability, and exposure. These three factors determine risk and interact with climate systems (natural variability and anthropogenic climate change) socio-economic processes, and emission and land use chance (Oppenheimer, 2013). In an enhancement, the current assessment outlines expanded scope of these three risk determinants and emphasizes responses that modulate each of these determinants (IPCC4, 2022). Therefore, the secondary factors influencing three determinants are now more stressed in analyzing the risk of a system. The risk, thus, defined and placed in the overall conceptual framework, according to AR 5, takes two major forms — key and emergent risks. The key risks are the direct and severe consequences; a vulnerable system confronts a hazard. On the other hand, emergent risks are indirect consequences of a hazard resulting from the responses to climate change (e.g., migration due to drought). Spatial linkages and temporal dynamics in the reaction to climate events are the major determinants of emergent risks (Rama *et al*., 2019)

Vulnerability to Climate Change

The vulnerability concept and its assessment first originated in natural hazards research (Marco and Ostrom, 2006) and subsequently evolved to be integrated into climate science. In recent research discourse, vulnerability to climate change (climate vulnerability or climate risk vulnerability) is one of the major components of risks for quantification and assessment. The third IPCC assessment report first time defined vulnerability as "the degree to which a system is susceptible to and unable to cope with adverse effects of climate change, including climate variability and extremes". Vulnerability secured a pivotal place in the climate crisis studies since the correct capture of this parameter has a huge implication on policy design. The first step toward climate change adaptation is to reduce vulnerability to current climate extremes (IPCC, 2014). The evolving concept and expanding boundary of vulnerability can be observed in the first IPCC AR report and its subsequent editions till the recent AR 6 report. There are two approaches widely followed to conduct vulnerability analysis and both of them have quantitative leaning. First, the endpoint or outcome method where vulnerability is mapped through a pre-post exercise after a system is affected by a hazard. Research works with this approach usually take place following a hazard. Damage assessment is an important exercise under this approach. A system that showed better resistance post a hazard is considered less vulnerable. Conversely, the starting point approach — most commonly used — intends to measure the pre-existing level of a vulnerability that a system is exposed to. The results obtained from starting point approach, typically identify the current gaps and weakness and their sources in a system where course correction measures are required. Thus, this approach is policy-relevant and worthwhile in the plan and operation of preventive measures against a possible hazard. Vulnerability is often read with concepts like community resilience, the marginality of a system, susceptibility, adaptability, fragility, and risk (Liverman, 1990). Of late, the concept of vulnerability is gradually expanded to be directly linked with exposure, sensitivity, coping capacity, and criticality (Füssel, 2007)

The UNDP (2004) distinctly classified four groups of vulnerability factors — social, economic, physical, and environmental. While social factors largely include population and its characteristics, economic factors focus on the resource endowment of the community or individual relevant to the assessment of vulnerability, especially in disaster risk reduction. Contact with the vulnerability-causing components is considered a physical factor and all environmental parameters are closely linked to ecology and the environment. Thus, appropriate measurement of the vulnerability requires a balanced analysis of both biophysical and socio-economic factors.

Since the third AR of IPCC, vulnerability was adequately defined and elaborated in a methodical framework and subsequent assessment reports of IPCC (till the most recent one) have further elaborated the components, but the core definition remains unaltered. Vulnerability here is presented as a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, 2001). Mathematically, vulnerability is often expressed as:

> Vulnerability = f (Exposure, Sensitivity, and Adaptive capacity). The three components that determine the degree and direction of vulnerability occupy an extensive significance in climate research. IPCC has acknowledged the differing views in contextualizing vulnerability and recognized it may differ across societies and time (Jurgilevich, Räsänen and Juhola, 2017; Kienberger, Blaschke and Zaidi, 2013). Exogenous, biophysical, and social dimensions of vulnerability are the key evaluation elements in vulnerability studies.

Exposure in this context is defined as the "presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected" (IPCC, 2014). Glick, Stein and Edelson (2011) defined sensitivity as the degree to which a system is affected, either adversely or beneficially, by climate variability or change. Adaptive capacity is the ability of a system to deploy management strategies for the reduction of risk associated with climate change (Heltberg, Siegel and Jorgensen, 2009).

Füssel and Klein (2006) further integrated this model by combining the first two elements - exposure and sensitivity and named potential impact. Thus, according to them, the vulnerability function is represented as:

> Vulnerability = f (Potential Impact and Adaptive capacity). However, the vulnerability equation developed by IPCC is widely employed and referred to in contemporary research.

According to Doch, Diepart and Heng (2015) vulnerability studies combine the social and biophysical aspects of environmental change. Füssel (2007) further elaborated on the classification of vulnerability factors. He categorized these factors based on scale and discipline. According to him, all factors causing vulnerability can be of two scales — internal and external. Furthermore, these factors can be categorised into two distinct domains — socioeconomic and biophysical. The classification of vulnerability factors is presented in table 1.

Table 1: Classification of vulnerability factors

Scale	*Domain*	
	Biophysical	*Socio-economic*
Internal	Sensitivity — land, topography, climatic conditions	Adaptive capacity — family income, social inclusion, access to information etc.
External	Exposure — large disaster (Tsunami, earthquake) sea level rise	Policy priority, political environment, the economic stability of the state etc.

The IPCC-given vulnerability equation is widely followed for quantitative measurement of these parameters. The term exposure in the equation denotes the degree to which a system is exposed to a climate event, while the adverse or beneficial impact resulting from climate variability or change is stated as sensitivity. Both exposure and sensitivity are positively correlated with vulnerability. The adaptive capacity of a system or individuals is to adjust to potential damage, take advantage of opportunities, or respond to consequences (IPCC, 2014). These three interconnected elements of exposure, sensitivity and adaptive capacity are represented by multiple relevant biophysical and social factors with the first-order connection with vulnerability.

The Research Practice and Progress

In view of the enormity of vulnerability as a research theme, different approaches have been attempted to explore and broaden this subject matter. Researchers in the past have contextualized vulnerability in a specific study domain e.g., household, ecology, livelihood, poverty, etc., and illuminated the process and factors that determine the magnitude of vulnerability. "Vulnerability assessments should include a predictive function (Naudé, Amelia, and McGillivray, 2009) to define vulnerability in relation to a socially acceptable level of outcome". Frankenberger *et al.* (2002) stated that easy and feasible data disaggregation and integration are important to measure at the regional and national levels. However, data deficiency is often a challenge in vulnerability assessment, especially in developing countries (Naudé, Amelia, and

McGillivray, 2009). USAID in 2013 observed that data feasibility, reliability and utility must be adequately met for an index-based measurement of vulnerability.

Selection and employing a particular approach should ideally be based on the purposes, contexts, and resources of the assessment.

Agricultural Vulnerability: The concepts and framework

The specific case of vulnerability owing to climate extremes has challenged farm outputs globally. However, this is a comparatively new research discipline gaining momentum in recent times. Agriculture is the base for food security globally and livelihoods for millions of rural households, particularly in the agrarian economies of developing countries. There is mounting burden from the increasing population to produce more food from fewer resources like land. Moreover, the rapid aberration of climatic factors has threatened the crop productivity of all major crops (IANS, 2022). Thus, a huge challenge worldwide today is to produce more food from lesser resources in the face of a productivity-limiting climate crisis. Such a predicament has intensified the research on agriculture-specific climate vulnerability. In countries like India and Bangladesh, the impact of climate on agriculture is even more pronounced since rainfed farming, fast depletion of groundwater, and shortage of farm labourers are coming due to out-migration (Kareemulla, Venkattakumar and Samuel, 2017). .

The generally accepted definition of agricultural vulnerability is how an agricultural system is prone to damages and losses due to the probability of climatic events. It is the degree to which the system (the crops and farmers) is susceptible, and cannot cope with adverse effects of extreme temperatures, drought, cyclones, flooding, storm surge, and other climate extremes that supposedly arise out of climate change. The predisposition of individual farmers or groups along with coping capacity determines the severity and extent of agricultural vulnerability (Palanisami *et al.* 2010). Agricultural vulnerability in climate science focuses on the physiological impact on crops resulting from climate extremes or variability. The socio-economic factors, such as education, household wealth, crop insurance, etc., constitute the adaptive capacity that negatively interacts with vulnerability level.

The evolving body of knowledge around suggests agriculture system is impacted by its climate vulnerability in three major ways. First, alterations in temperature and precipitation resulting from climate change can cause variation in cropping patterns. Second, because of climate extremes (drought, flood, soil salinity), crop productivity is reduced and lost. Third, farm income is considerably affected, and livelihood is adversely impacted that brings down the adaptive capacity and makes agriculture more vulnerable (Mitter *et al.*, 2014). Thus, analysis of agricultural vulnerability assumes huge policy implications where the peasantry is a mass occupation. Like general vulnerability exercise, agricultural vulnerability manifests through the interaction of environmental and socio-economic processes (Berry *et al*., 2006). Noticeably, a large body of research works is inclined toward the analysis of climate factors with lesser stress on investing socioeconomic parameters (Wu *et al.*, 2017). The combination of a climate and socioeconomic perspective to look into agricultural vulnerability is lacking in the current research discourse (Dwarakish, Vinay and Natesan, 2009)). In addition, the majority of the available studies on agricultural vulnerability analysis in India have focused on the predicted effect of climate variation (Panda, 2017).

Komali (2016) identified three major research gaps in the assessment of agricultural vulnerability. First, in the Indian context, the existing research efforts are largely concentrated on assessing drought and its consequences; the vulnerability associated with farming in coastal areas is markedly ignored. Moreover, the usage of primary data and a combination of quantitative and qualitative tools is limited. Secondly, the deficit in efforts to factor both climate and the socio-economic parameter is now noticeable. Finally, the research in its current pattern is spatial in nature largely while ignoring the time factor. Thus, the insight into how vulnerability has responded and evolved is insufficient and temporal analysis needs more research attention. The approaches to study the climatic vulnerability also vary depending on the context, nature of the vulnerability and research objectives. Table 2 presents a brief account of the commonly followed vulnerability study approaches.

Table 2: Approaches to vulnerability studies

Vulnerability approach	*Proponent*	*Definition*	*Purpose*	*Major features*	*Benefits*
Household vulnerability index (HVI)	FAO and Natural Resources Policy Analysis Network (FANRPAN, 2004), South Africa	Vulnerability is the “presence of factors that place households at risk of becoming food insecure or malnourished	Used to measure vulnerability at the household level in HIV-hit areas.	Identification of most vulnerable and sustainable ways to assist vulnerable Monitoring food security during a vulnerable context (Kureya, 2013)	15 “impact areas” of vulnerability are assessed using indicators
Local Vulnerability index (LVI)	Naude, McGillivray and Roussouw (2008)	It measures subnational regional vulnerability to identify “spatial poverty traps” and covariate risks	Improves vulnerability assessment methodologies	Captures regional variation of the vulnerability and identifies spatial poverty gaps. It employs principal component analysis (PCA) and extracts the most relevant factors causing vulnerability. The index is helpful for regional	Status of the local economy, international trade capacity, peripherally, income volatility, demography and health, environment and geography, and the financial system are the evaluation indicators

Vulnerability approach	*Proponent*	*Definition*	*Purpose*	*Major features*	*Benefits*
				planning with an estimated level of vulnerability.	
Household Livelihood Security Analysis (HLSA)	Developed in 1994 by CARE as framework for program analysis, design, monitoring and evaluation" (Frankenberger, Mock and Jere (2005)	It is asset-based, and multidisciplinary to widen the understanding of livelihood vulnerability (Cannon and Twigg, 2005).	Originally the analytical framework used only PRA and RRA tools, later quantitative surveys were included to assess the vulnerability based on a reasonable sample	It measures the attainment of a geography on economic security, food security, health security, educational security and empowerment. Extensively used qualitative techniques to understand vulnerability hence should be generalized carefully.	The analysis is used to capture the change an intervention created in the target geography
Household Economy Approach (HEA)	A livelihood based methodical framework by Save the Children UK (Holzman *et al*., 2008)	Forecast the potential impact of a disaster across different income groups	Widely used by National Vulnerability Assessment Committees in southern Africa (SADC FANR Vulnerability Committee, 2004)	It is a mixed method approach, includes quantitative secondary and primary data, and employs participatory and qualitative techniques to generate qualitative insights. It guides who, where needs responses during a disaster	It requires extensive disaggregation of data for vulnerability mapping at individual and household levels. Strong inclination to qualitative tools and non-probability sampling, dilutes, at times the statistical validity of the findings
Social vulnerability	Brooks (2003)	Describe all the factors linked to a potential hazard of	Strong emphasis on social capacity of the	Social vulnerability encompasses physical	Social factors are highly focused

Vulnerability approach	*Proponent*	*Definition*	*Purpose*	*Major features*	*Benefits*
		a certain nature and severity.	community take on a vulnerable situation	environment like soil topography, water reservoirs, land characteristics etc. that determine the outcome of a hazard	

Methodical Approach to Vulnerability Research

The experiment on vulnerability in the context of agriculture is carried out by employing different research methodologies deemed fit by the researchers. Selection of a methodology is often guided by the research purpose, nature of the problems and end users' requirements. Besides, time, resources and data availability especially in developing countries are important consideration in selecting a best-fit method (Naudé, Amelia and McGillivray, 2009). All the methods have their own benefits and certain shortcomings, but nevertheless, some in several ways, are robust based on sound reasoning, and explore scientific facets to conceptualize agricultural vulnerability and its complexities. Though index-based methods are most commonly employed, there are other handful techniques to capture and analyse the concept of climate vulnerability. The plurality of technical dimensions in assigning weight to the climate variables is also observed. Contemporary agricultural vulnerability research is more inclined towards quantitative calculation. However, when such quantitative studies are complemented by qualitative tools, the research results becomes more accurate and reliable (Banerjee, Duflo and Chattopadhyay, 2007). An account of major methodologies being followed in contemporary vulnerability research specific to agriculture is presented below (Table 3).

Table 3: Major methods for vulnerability research in agriculture

Methodology	*Method description*	*Major advantage and disadvantage*
Descriptive methods	Descriptive methods identify key vulnerability drivers and nature, frequency and intensity of climate events and their adverse impacts on agricultural systems. Such a methodology emphasizes to map a geography based on the attainment of different climate parameters and then categorization of different regions based on the threshold marks is used to depict the spatial vulnerability (Kelly and Adger, 2000). Interdependence of vulnerability	*Advantages* -This is the simplest way to present vulnerability of an area -It encompasses several qualitative information *Disadvantages* -Normally it is void of metric measurements, thus it is not quantitatively tenable at times.

Methodology	*Method description*	*Major advantage and disadvantage*
	parameters are not deeply covered, however detailed account of vulnerability causing triggers are researched and documented.	
Analysis of variance	For long, analysis of variance of important weather and production parameters served as standard research methods to capture and analyse the extent of vulnerability. Quite often, fluctuation in rainfall, temperature, humidity and the trend of agricultural production were correlated to quantify the vulnerability and its impact. Furthermore, the crop production is regressed against vulnerability causing weather parameters to build a causal relationship which reveals the facets of vulnerability (Liang, Zhang and Qin, 2021).	*Advantages* -Easy to conceptualize and assess -Normally, data is available. *Disadvantages* The major disadvantage with this method is Interdependence of vulnerability parameters is usually not deeply investigated.
PRA techniques	Participatory rural appraisal techniques (PRA) are widely followed qualitative techniques to generate social perspective about community vulnerability, its dimensions, impact and interplay with other socio-economic factors. Conventionally, such tools are employed before or after any planned quantitative exercise. Qualitative insights built through these participatory tools consummate the research conclusions obtained in quantitative studies (Kang and Holbert, 2005). Under this technique, risk analysis, resource map, mobility mapping, vulnerability maps, resource maps are sketched to build the understanding about vulnerability.	*Advantages* -In-depth analysis and building community perspective, which are insufficiently captured in metric measurements. -It helps in formulating community-centric adaptation measures *Disadvantages* -PRA techniques are highly focused on qualitative assessment -Conduct of PRA methods come with several operational challenges e.g resources requirements, constraints to organize many PRAs
Indicator based computations	Indicator based measurements are the most common methodology in vulnerability research. In line with the IPCC method, three vulnerability components are exposure, sensitivity and adaptive capacity. However, each of these components encompasses a different set of indicators based on the	*Advantages* -Metric measurements, makes the analysis objective, easily comprehensible and comparable across times and space. -The vulnerability

Methodology	*Method description*	*Major advantage and disadvantage*
	research areas e.g., indicators under exposure for agriculture vulnerability study will supposedly vary from that of a livelihood vulnerability analysis. Since the data metrics of different indicators are in different units, first those that are normalized (mostly by HDI method) and then appropriate weightage is assigned. One methodical argument in this index-based measurement is fixation of weightage to different selected indicators under each of those components. Many researchers tend to distribute weightage equally. However, for statistical robustness and research logic, many scientists now follow Iyengar-Sudarshan vulnerability index (Kumar, Solmon and Vishnu-Sankar, 2014)) equation since the weights vary inversely with variance over regions in the respective indicators on vulnerability. In other cases, researchers use the fuzzy-AHP technique in assigning appropriate indicator-weightage (Larrhoven and Pedrycz, 1983). Based on the research objectives and experimental type, selection of components differs. In another indexation technique, vulnerability index is constructed by combining relative rating assigned to identified risk variables (e.g sea level change) according to their varying ability to cause damages (e.g., 1 for low, 2 for medium, 3 for high). Mathematically, the vulnerability index is calculated taking square root of product of rating of all risk variables divided by the number of variables. (Pendleton *et al*., 2004).	components are adequately defined and followed by researchers across the globe, thus indexation with those components is broadly accepted. -Based on sound mathematical reasoning, thus widely accepted among key stakeholders -Highly data centric, thus, making the experiment more evidence based. *Disadvantages* **-**Fixation of indicators and assignment of weightage are sometimes subjective and thus accepted or criticised by different groups of researchers. -At times, such indexation has computational complexities that deter researcher to fully employ these methods.
Simulation method	Several crop growth simulators and climate change models have been developed by scientists to observe the crop growth responses to changing climate, soil and other management	*Advantages* -image based simulation of climate events, therefore credible and highly scientific

Methodology	*Method description*	*Major advantage and disadvantage*
	factors. Such simulation-based models help in projection of climatic events and the possible impacts. Besides, GIS based images are often used to map regions based on intensity, frequency and nature of the climate events as captured by satellites. Some of the models previously used for the vulnerability assessment are: The Crop Environment Resource Synthesis (CERES) for wheat. PRECIS is developed at the Hadley Centre at the UK Met Office. EPIC plant growth model (Tao, Xu and Liu, 2011).	-With satellite images, vulnerability can be depicted for any target area *Disadvantage* -Purely account for climate factors, socio-economic scenario is ignored in vulnerability studies. -Access to images is expensive thus restricting the reach of the researchers.
Objective and quantitative assessment method	This analytical tool was recently proposed by a group of researchers from China Agricultural University. In this method, unit vulnerability is measured as the ratio of sensitivity and adaptive capacity. It further computes two types of yields — crop yield (normal) and sensitive yield (yield during climate shocks). The reported difference between these two yields defines the adaptive capacity in the region. Exposure degree is defined by the ratio of the crop area in the study period and the average planting area reported in a base year, which shows spatial scale of the climate effect. Thus, agricultural vulnerability is computed as Sensitive yield divided by adaptive capacity and exposure degree (Hhiqiang *et al.*, 2015)	*Advantages* -This is a relatively new metric method to quantify agricultural vulnerability, which opens up a new metric measurement to assess vulnerability. -Purely quantitative measurement and data driven *Disadvantage* -The measurement doesn't include social aspect in the vulnerability analysis.

Discussion

The Trend of Agricultural Vulnerability Studies

In line with the general vulnerability measurement, agricultural vulnerability studies are largely quantitative and index-based assessments. Scientists, based on the previous studies and research objectives, select and define relevant indicators distributed across social and climate domains. It has become a common practice to measure vulnerability to climate change or natural hazards in several sectors (tourism, energy and finance), including agriculture (Kalli and Jena, 2022). The index constructed after indicator standardization and assignment of weightage lends itself to spatial and temporal comparison.

The first structured study on agricultural vulnerability can be traced back to 1989 when Gornitz and Kanciruk (1989) mapped and developed an index to evaluate the vulnerability of coastal regions of the United States. Hareau, Hofstadter and Saizar (1999) studied the agriculture, industry and service sectors of Vietnam and developed vulnerability indices applying Iyengar and Sudarshan method[1]. Gbetibouo and Ringler (2009) used 19 indicators for exposure, sensitivity, and adaptive capacity to map South African farmers based on agricultural vulnerability to climate effects. Kumar, Kumar and Kunte (2012) developed a coastal vulnerability index by considering eight indicators to estimate coastal vulnerability to physical changes emanating from the future rise in sea level. Huq, Boon and Gain (2015) analyzed the impacts of climate change and other pertinent factors on coastal agricultural communities with soil erosion as an adverse consequence. He made a scientific account of three orders of the impact of agricultural vulnerability. Shukla, Kamna and Joshi (2016) studied the mountainous region in the Himalayas and assessed the inherent vulnerability of agricultural communities. In 2017, Panda (2017) constructed an index to enumerate farmers' vulnerability to drought. Jose *et al.* (2017) evaluated the vulnerability of crops to floods in the Philippines. They grouped physical, agroecological and socioeconomic indicators under the components of exposure, adaptive capacity, and sensitivity. Komali *et al.* (2018) observed that coastal vulnerability as a research aspect is understudied and more attached to geomorphological and, to an extent, socioeconomic domain. They, in England, constructed a physical coastal vulnerability index and compared it with a fiscal coastal vulnerability index to form a combined coastal vulnerability index. Kantamaneni *et al.* (2018) developed Combined Coastal Vulnerability Index CCVI to compute vulnerability using physical and fiscal parameters. Ducusin *et al*. (2019) did an extensive research to scientifically illuminate vulnerability as a function of exposure sensitivity and adaptive capacity using a total of 28 indicators. The study conclusively found terraces to be moderately vulnerable, mostly in sensitivity and adaptive capacity, to climate change extremes. Sneessens *et al*. (2019) designed an analytical framework to assess the financial vulnerability of farming systems. They implemented the framework in French farms and showed that diversification alone is not a risk-mitigating strategy. Less vulnerable mixed crop-livestock systems create less dependency on markets. Bangladesh is one of the countries. Mahmood *et al*. (2020) applied RS and GIS techniques and constituted a coastal vulnerability index (CVI) to suggest intervention areas along with the Meghna coastal areas in Bangladesh. In 2019, Sekovski, Rio and Armaroli (2019) experimented with and designed an index of physical vulnerability caused by sea-level rise and marine floods in the low-lying coastal area of Ravenna Province in Italy. In Nile delta of Egypt, Mohamed (2020) used GIS-based multi-criteria analysis and mapped the relative coastal vulnerability level in the form of an index (CVI). A significant portion of the shoreline was found to face a moderate to the high degree of vulnerability.

[1] After indicator value normalisation, the Iyengar Sudarshan vulnerability index equation was applied and in the index weights are assumed to vary inversely with variance over regions in the respective indicators on vulnerability. For further information on this can be accessed from http://ir.cut.ac.za/bitstream/handle/11462/2122/J79%20%20%20Iyenga%20Sudershan.pdf?sequence=1&isAllowed=y

Research Gaps and Future Priority Settings

Climate change is a fast-evolving phenomenon and, thus, vulnerability analysis is a research priority. Globally, the concept of vulnerability and its measurement approaches are rapidly evolving due to the growing impact of climate change. During the last two decades, agricultural vulnerability has gained high research attention; therefore, the research approaches and analytical framework have been going through a fast transformation. The development and implementation of different research approaches and techniques have not only strengthened the subject matter but also encouraged researchers to deeply experiment and explore its subtlety and nuances. The policy measures adopted by vulnerable regions are often aided and guided by the findings and recommendations of vulnerability research. However, like many other disciplines, agricultural vulnerability analysis is seriously constrained by a set of challenges that warrant scientific redressal to fortify vulnerability studies. Multitude of definitions, assessment approaches and application of several methods to depict the "vulnerability" and "adaptation" is a concern and it is related to complex nature of climate impact and strategies used to deal with them (Bedeke, 2023). Ishtiaque *et al.* (2022) highlighted concerns in conceptualizing of 'vulnerability', as introduced in the IPCC Fifth Assessment Report (AR5) and it has not been well accepted by the vulnerability researchers. Farmers' perception about the climate vulnerability also differs spatially. However, majority of the Indian farmers have perceived a risen temperature, and erratic and decreased rainfall are vulnerability indicators (Datta *et al*., 2022)

Defining Vulnerability in Research

The vulnerability of the whole agriculture system (including livestock, fisheries, etc.) is a broader research theme and needs to be differentiated from the vulnerability of just crop production in a region. Even within crop outputs, all-important crops having a major share in the farm outputs should be included for analysis purposes. Thus, type of vulnerability for research needs to be precisely defined and stated.

Indicator Selection and Weightage Assignment

Choice of indicators for different variables of sensitivity, exposure, and adaptive capacity needs to be executed through a statistical process. Arbitrary selection of a set of indicators without sufficient scientific exercise may dangerously mislead the analytics. There is a noticeable gap in this particular aspect that is to be reflected in future research. The growing deliberation on labour productivity loss owing to climate change has far-reaching consequences to making agriculture vulnerable. Future research should be more focused to investigate and bring out the factual information in suggesting remedial measures.

The climate change vulnerability index is used to assess the vulnerability of humankind to extreme climate events and variations in climate over the decades (Rana *et al.,* 2021). Several vulnerability studies are biasedly focused on biophysical parameters and unreasonably discount social dynamism rooted in gender, social class, economic capacity, and social cohesion of a community (Dong *et al.*, 2015). This is more relevant while agricultural vulnerability is studied since social dynamics in a rural area is a prime determinant of vulnerability. The shifting focus from a natural ecosystem to an integrated system (socio-ecological) focus of the research will be more representative of vulnerability (Li *et al*., 2013). The collaborative research engagement between climate scientists and social researchers will enrich the studies and make them multidimensional. Vulnerability assessed through a perfect combination of bio-physical and socio-economic factors will be experimentally robust and holistic to present the real life scenario.

Researchers also need to be cautious to differentiate between underlying and manifest indicators for correct representation and avoidable duplication of risk variables. To cite an example if opting for crop insurance is recorded as an indicator of adaptive capacity, further inclusion of awareness and education about crop insurance as a variable perhaps will not add value but rather increase the load of the vulnerability model. Each indicator has a varying contribution to the combined vulnerability index. The relative importance of different indicators and assigning weightage accordingly is also tricky and generally subjective. For instance, an area with sufficient irrigation facilities is supposedly not impacted much by rainwater deficit, unlike a rainfed area. Therefore, the relevance and significance of an indicator need to be contextualized under different circumstances for appropriate weightage allocation. Expert analysis often used for this purpose is unavoidably biased, thus, increasing the application of better techniques, such as AHP analysis, artificial neural network techniques, weightage fixation. In the times to come, research should be directed to eliminate disadvantages associated with these methods and facilitate to building and apply more scientific techniques.

Contribution of Components to Vulnerability

Contemporary vulnerability researchers largely adopt IPCC analytical framework and evaluate it on three major components — sensitivity, exposure, and adaptive capacity. The estimated combined score quantifies the vulnerability magnitude; however, there is a substantial research gap in decomposing the contribution of these three components to the overall vulnerability measurement (Eddoughri *et al.*2022). This is essential in formulating targeted policy measures to reduce vulnerability. The research discourse should set the priority on this particular aspect.

Data Constraints

Metric measurement of agricultural vulnerability sets a precondition of access to quality of data on different indicators. Such datasets in advanced countries are well managed and in use for multiple purposes. However, data constraint is a serious challenge in developing nations where scientists struggle to access the data, even where it is available, quality is always a concern (Choudhary and Sirohi, 2022). This particular constraint can be mitigated with scientific storage and management of key indicators data to enrich future studies on agricultural vulnerability.

The Mixed Method in Vulnerability Analysis

There is a growing consensus to adopt a mixed method to study a subject matter like agricultural vulnerability and it necessitates the importance of employing qualitative approaches and techniques. The application of the participatory rural appraisal technique offers tremendous advantage of validating conclusions generated in the quantitative section. The robustness, reliability and acceptability of vulnerability research increase when results are substantiated through a combination of the research approaches.

Conclusion

In the coming years, the research on the vulnerability of agriculture due to climate change will see innovation, enhancement, and development in adopting holistic multidisciplinary approaches to emerging research and policy questions. The scope of vulnerability and its components will be widened and measured through robust scientific methods. However, selection and application of a particular approach should be guided by the nature of the research problem and contextual comprehension of the research needs. However, in depth analysis of the research questions shall be the guiding principle to adopt approaches for studying vulnerability. In case of agricultural vulnerability, it has its own computation challenges because of the nature of indicators and their measurements. Elements that constitute vulnerability in agriculture in a particular context remain contentious. Therefore, further standardization of measurement methods and research approaches are strongly advised. Selection of methodology is critical, as it has bearing on accuracy and robustness of the assessment. The increasing application of simulation methods and software-enabled assessment should be further refined and adjusted for real time quantification of vulnerability with higher degree of accuracy. The importance of people's perception about vulnerability in agriculture is another area often ignored and under-represented in vulnerability model. The participatory appraisal tools can be beneficial in defining and then assessing vulnerability in agriculture. The paucity and inaccuracy of data pertaining to selected indicators is an impediment to estimate correctly the extent and intensity of vulnerability, especially when measured for smaller geography. Nevertheless, such challenges can be significantly overcome by employing a mixed method of analysis including participatory rural techniques. These will contribute to the ultimate purpose of enriching the discipline with a fast-paced scientific innovation in the concept, content, and quantification of agricultural vulnerability.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*
Conceived and designed the research or analysis	Yes	Yes	Yes
Collected the data	Yes	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	Yes
Wrote the article/paper	Yes	No	No
Critical revision of the article/paper	Yes	Yes	Yes
Editing of the article/paper	Yes	Yes	Yes
Supervision	Yes	No	No
Project Administration	Yes	No	No
Funding Acquisition	No	No	No
Overall Contribution Proportion (%)	60	20	20

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals not even indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge

The author(s) solemnly declare(s) that this research has not involved any Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge are only indirectly covered, if any, through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved the plants for experiment or field studies. The contexts of plants are only indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

(Optional) Research Involving Local Community Participants (Non-Indigenous)
The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people are only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

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The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

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