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A review and synthesis of the Consultative Group on International Agricultural Research's work on climate-induced extreme rainfall and floods, 2012–2023

Claudious Chikozho[1*], A. Mukherji[2], C. Bosire[2], K. Kujinga[3] and R. Managa[4]

Abstract

Background In recent decades, the increased frequency of extreme rainfall events has significantly affected agri-food systems, accounting for 19% of the total crop damage across the world and 18–43% of observed anomalies in global crop yields. Some studies indicate a global weighted mean rice yield loss of 9.0% by 2080 under a high-emissions scenario. In sub-Saharan Africa, crop yield losses from extreme rainfall can vary significantly, with one source citing a 33% reduction over the past 60 years due to climate-induced weather extremes, including floods. It is estimated that in Africa, about 12% of the people that experienced food insecurity from 2009 to 2020 had their food security status affected by flooding. The Sixth IPCC assessment report warns that climate change could push an additional 32–132 million people into extreme poverty by 2030 if the world does not immediately scale up adaptation solutions. This review articulates the CGIAR's contribution to scientific knowledge on climate-induced extreme rainfall for the period 2012–2023. The review discusses research methods applied, main impacts of extreme rainfall on agri-food systems, and innovative adaptation solutions deployed.

Results Out of 2846 identified papers, 73 studies met our search criteria and were included in the review. Our analysis reveals that the main impacts of extreme rainfall addressed by the CGIAR include physical loss of crops due to coastal area inundation, waterlogging, and salinity intrusion. Adaptation options that build the resilience of smallholder farming systems include scientific methods for forecasting changes in rainfall patterns; flood early warning systems; climate-smart agricultural technologies; flood-resilient seed varieties; and agroforestry. However, lack of finance and knowledge tends to limit smallholder farmers' ability to adopt some of the technological innovations, suggesting the need for capacity building and policies for better access to microcredit, low-interest loans, and climate risk insurance schemes. Research gaps identified in the study call for the CGIAR to also focus on currently underexplored themes such as roots and tubers, livestock, fish, and peri-urban agriculture. The integration of attribution studies that address direct links between extreme rainfall and climate change could inform targeted interventions arising from CGIAR research. Studies that specifically quantify economic losses from floods could also generate important insights for effective agricultural investment and risk management.

*Correspondence:
Claudious Chikozho
c.chikozho@gmail.com

Full list of author information is available at the end of the article

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Conclusion This review identifies key areas of focus and critical knowledge gaps to be addressed by future CGIAR research. It informs the agenda of decision makers and policy makers who grapple with the challenges of scaling adaptation solutions to strengthen farmers' resilience to extreme rainfall.

Keywords Extreme rainfall, Impacts, Adaptation, Vulnerability, Waterlogging, Food security, Resilience

Introduction

In recent decades, a rapidly changing climate has increased the frequency and intensity of extreme rainfall and floods, and in the process, worsened risks faced by farmers [30]. The Intergovernmental Panel on Climate Change (2023) states that human-induced greenhouse gas emissions have led to an increased frequency and intensity of all weather and climate extremes. This is evident from assessments looking at pre-industrial times, where temperature extremes show global surface temperature reaching 1.1 °C above 1850–1900 levels in 2011–2020 (IPCC, 2023) [38]. This has also triggered other changes in the frequency of extreme weather events that have become widespread since the 1950 s, including intensification in global-scale extreme precipitation and tropical cyclones (IPCC, 2021) [37]. At the global scale, the intensification of heavy precipitation will follow the rate of increase in the maximum amount of moisture that the atmosphere can hold as it warms (*high confidence*) of about 7% per 1 °C of global warming (IPCC, 2023) [38]. This suggests that farmers will also need to continue adapting in response to escalating shifts in climate change impacts over time.

As an analytical construct, *extreme rainfall* may be defined as rainfall that is greater-than-normal in terms of its intensity and amount, falling within a specific period of time, and in some cases resulting in floods and other negative outcomes such as waterlogging, coastal inundation and destruction of crops [15, 27]. Such events are characterized by heightened intensity and duration of rain, and can lead to various hazards such as flooding and landslides. Some scholars define extreme rainfall as rainfall that is greater than 100 mm and falling within twenty-four hours ([22]; IPCC, 2021) [37]. Experts are now able to calculate the extreme precipitation days index, which counts the number of days in a year when the daily rainfall exceeds a certain threshold, with a some amount of damage being expected to occur [28].

Extreme rainfall and floods cause enormous damage to food production all over the world and especially so in South East Asia and East Africa [16]. In the agriculture sector, floods now account for 19% of the total crop damage across the world, in comparison to other sources of damage such as storms, pests, diseases, infestations, and wildfires in developing countries (FAO, 2021) [26]. A study by Yolchi et al., [72] in rural Afghanistan concluded that flood exposure increases the Household Hunger Scale by 0.77 points and significantly raises the probability of moderate and severe food insecurity by 11% and 20%, respectively. Akpa, [3] states that crop yield losses from extreme rainfall in sub-Saharan Africa can vary significantly, with one source citing a 33% reduction in crop yields over the past 60 years due to climate change-related weather extremes, including floods; other studies highlight specific impacts, such as a potential 13% reduction for major cereal crops in a worst-case scenario for West and Central Africa.

In general, negative impacts of extreme rainfall on agri-food systems often arise from widespread flooding, severe soil erosion, increased risk of landslides, waterlogging, direct damage to crops, loss of livestock, reduced crop yields, increased outbreaks of pests and diseases, and nutrient leaching; all this ultimately leads to potential crop failures and economic losses for farmers [1]. The regions in which the Consultative Group on International Agricultural Research.

(CGIAR) does research such as Africa, Asia, and Latin America have already experienced the impacts of accelerating climate change, including extreme precipitation events. As the IPCC (2023) [38] points out, human-induced climate change is already causing many weather and climate extremes in every region across the globe. Extreme rainfall events have been shown to account for 18–43% of the observed anomalies in global crop growth and yields; the consequences of such yield anomalies include fluctuations in food prices, destabilized food supplies, and famine [29, 51].

Extreme rainfall often results in floods/flooding, which is an overflowing of water that ends up inundating or submerging land that is normally dry. During periods of high precipitation, increasing temperatures not only reduce the efficiency of photosynthesis, but also result in a faster development of crops; this leads to a shorter life cycle, resulting in smaller crops, then a shorter grain filling period, and finally, to lower yields. Once flood stress occurs, the limited function of root systems leads to weakened respiration and even root damage, while nutrient loss and soil erosion reduce nutrient supply, thus affecting crop growth [25]. At the same time, the increase in climate variability is likely to drive more frequent and severe flood events across the world (Mai et al., 2020) [46]. This suggests the need for a precise understanding of the frequency and magnitude of extreme rainfall events and their impacts on agri-food systems. This understanding would help in agricultural policy decisions and planning as well as water management operations.

Efforts should also be made to prepare site-specific disaster management plans to minimize the impacts of extreme rainfall and floods (Subash et al., 2011) [64]. In many cases, adaptation to the impacts requires both anticipatory and post-disaster interventions that enable affected communities to sustain their livelihoods [29, 43, 66]. This also implies that practical solutions are urgently needed to address these impacts. Figure 1 illustrates some of the impacts of climate change on crop yields in SSA. In addition, Annex 1 summarizes the known impacts of extreme rainfall and floods.

As the world's largest publicly funded research and innovation organization on agriculture and food systems, the CGIAR, has been addressing food security issues for more than 50 years in Africa, Asia and Latin America. The CGIAR launched its first dedicated Research Program on Climate Change, Agriculture and Food Security (CCAFS) in 2009. The program's climate-related publications started emerging by 2012 (the starting point of this review). This paper synthesizes CGIAR's publications on extreme rainfall and floods, examining their impacts on agri-food systems and the adaptation solutions developed or implemented by CGIAR to mitigate these effects. It also reviews the methodological approaches that were deployed to measure both the impacts of these extreme weather events and the effectiveness of the proposed solutions.

Objectives of the study

The main goal of this review is to assess the CGIAR's contribution to the knowledge base on climate change adaptation in the context of extreme rainfall and floods by systematically analyzing their publications. Main focus is on methodologies applied; major impacts on natural, agricultural and human systems; and solutions that may be strengthened or outscaled to promote food security. Specific objectives of the review are as follows:

(i) To quantitatively review and characterize scientific articles published by the CGIAR between 2012 and 2023, highlighting their main areas of focus, contribution to the physical science of climate-induced extreme rainfall, emerging trends, methodologies and concepts applied to understand climate-induced extreme rainfall, impacts and adaptation options.

(ii) To identify critical gaps in CGIAR's climate research and provide actionable insights that may inform future research priorities and improve the resilience of agrifood systems to climate change-related extreme rainfall and floods.

It is important to point out that key stakeholders in the agricultural development sector increasingly emphasize the need to deploy rigorous evaluations and comprehensive knowledge synthesis processes to determine the impacts and outcomes of any new socio-technical solutions and interventions. Therefore, consolidating

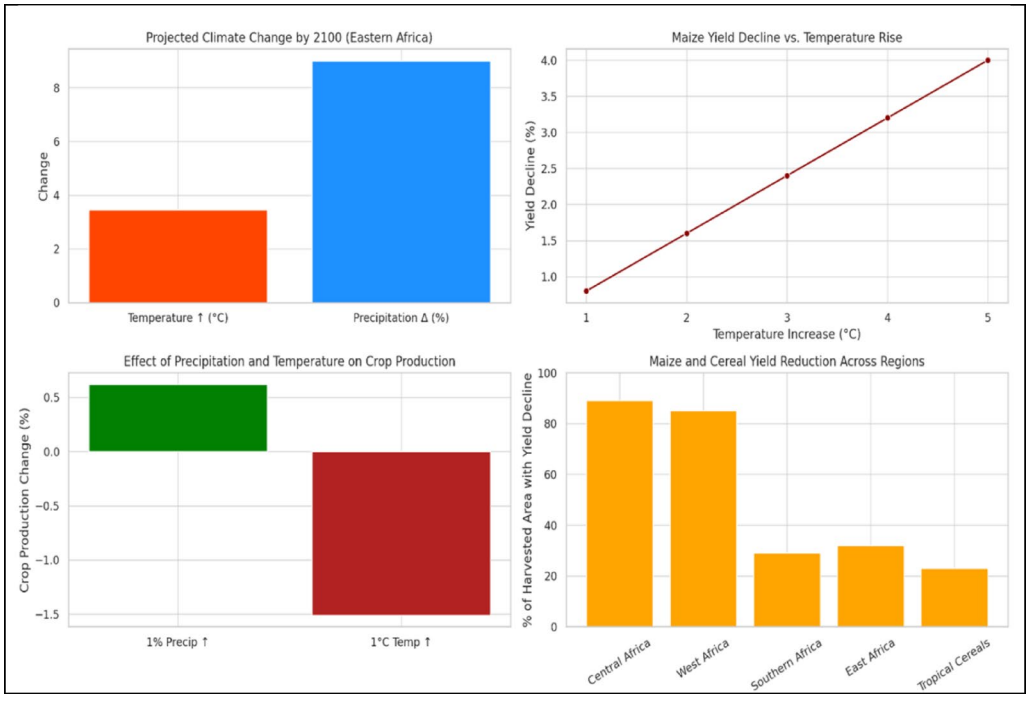


Fig. 1 Impacts of climate change on maize and crop yields in sub-Saharan Africa

research on climate-induced extreme rainfall and floods within the CGIAR can help in identifying potential entry-points for scaling impactful interventions that have been documented by CGIAR scholars in countries affected by this phenomenon. Recommendations provided in the review could be used to inform the development of more coherent strategic programs for addressing the impacts of extreme rainfall on agri-food systems and food security.

Review methodology

This review is based on an assessment and synthesis of evidence from CGIAR research published between January 2012 and December 2023 to understand the CGIAR's body of knowledge on extreme rainfall and its impacts on agri-food systems as well as the adaptation options for the same. This period is important in that it captures insights from the CGIAR's CCAFS program that started in 2009. Thereafter, the CGIAR as an organization started putting more emphasis on climate change research. To review and synthesize the relevant papers, we developed a study protocol that was based on a CGIAR analytical review framework that disaggregated the selected articles into three main areas of focus. These are the *methods* frequently used by the CGIAR researchers to study, understand, and forecast trends in climate-induced extreme rainfall and floods; observed and potential *impacts* of climate-induced extreme rainfall and floods on agri-food systems; and *adaptation solutions* recommended by most of the studies to address the impacts of extreme rainfall and floods on agri-food systems.

In essence, we followed the six steps that are commonly used in systematic literature reviews as described by Tawfik et al., [67]. These are: defining a clear research question to be addressed; developing a protocol to methodologically guide the review and synthesis; conducting a literature search using a comprehensive search strategy to identify relevant studies; screening the identified articles using clear, explicit, and consistent criteria in order to select articles that meet specified objectives of the systematic review; critically appraising the quality of the studies and assessing the risk of bias; and analysing the data, synthesizing and interpreting the results based on the evidence presented in the articles and making specific conclusions. However, one major difference from a standard systematic review is that we limited our review to only those articles in the CGIAR's climate change publication database, 2012–2023.

Literature search and screening process

To generate a database that is amenable to thematic area analysis of climate research in the CGIAR, the R-package version 3.5.0 topic modelling software was used to search the CGSpace climate research database that was developed by extracting literature from nine CGIAR institutional repositories. The search syntax principles for each repository were maintained as similar as possible, with only minor changes to accommodate search engine specific formatting. This method builds on topic modelling, which is an unsupervised machine-learning technique, instead of manually predefining topics. This process generated 20 topics that were considered relevant to climate change based on the wordcloud output. Three of the topics were directly relevant to the thematic area of extreme rainfall and floods. The papers from the three sub-topics led to the establishment of a dataset with 2850 articles that were subsequently used for this review. Further screening and analysis using Artificial Intelligence (AI) identified 444 papers that were directly relevant to our main topic. These papers were imported into the Rayyan software where a new project was created and duplicates were removed. Titles and abstracts were subsequently double-screened based on the inclusion and exclusion criteria specified in Table 1. The use of AI enabled faster screening of a large number of papers to identify the most relevant ones.

Relevant articles agreed upon by two reviewers were included, while conflicts were resolved through a second round of reviews and consensus on whether to include or exclude entries in the conflict category. The search and paper screening process is as outlined in the Reporting Standards for Systematic Evidence Syntheses (ROSES) flowchart (see Fig. 2).

The ROSES Diagram shows that a total of 107 articles were selected for full content review after the initial screening process conducted using title, key words, and abstract. We reviewed only those articles that explicitly address extreme rainfall and/floods. After the full content review, 34 articles were further excluded because they either mentioned extreme rainfall/floods in passing, did not directly address extreme rainfall/floods, or were quite peripheral to the theme of extreme rainfall/floods. This left a total of 73 articles for inclusion in the review covering countries in Asia, Africa, and Latin America (see additional file 1 for the list of articles).

Methods for data analysis

We used the OpenAI's GPT-4o-mini model software to query the selected papers in terms of their contents and major insights emerging therefrom. Among others, this included developing and answering pre-set questions such as what the study is about; whether it is about observed change or projected changes to precipitation; the geographical location of the study (continent/sub-region/country); and the type of study it is, particularly with regards to whether it focuses on methods for understanding extreme rainfall and floods, the impacts, or solutions thereof. We then reviewed and cross-checked all the answers to see if chat GPT had correctly analyzed

Table 1 Summary of key steps followed in carrying out the review

Population	All, humans, animals, and plants/crops
Intervention	•Research across various CGIAR centres (across commodities and topical areas) and linked to climate and impacts of extreme rainfall/floods as the principal topic
Control	None
Outcome	•Determination of main clusters of climate and extreme rainfall analysis in the CGIAR •Provision of options to address the gap between current research and proposed impacts •Effective programming by supporting the development of more coherent and strategic programs for addressing extreme rainfall and floods •Improved outcomes and impacts for communities and smallholder farmers through a synthesized body of research that facilitates the implementation of evidence-based practices for addressing the negative impacts of extreme rainfall and floods
Setting	Global climate research within the CGIAR
Eligibility criteria	**Inclusion criteria** •Type of article: Peer-reviewed journal articles focusing on the nature of climate-related extreme rainfall and floods written by CGIAR researchers •Time: Studies published between 1 January 2012 and 31 December 2023 •Topic: Published articles that directly address emerging trends on the intersection of climate change and extreme rainfall and impacts on agriculture/food security •Articles that describe the impacts of extreme rainfall and floods on agriculture and/food security at local and national levels in CGIAR focal countries. •Articles based on credible research methods •Articles that offer potential solutions for communities and smallholder farmers to mitigate and/adapt to the impacts of extreme rainfall and floods •Language: The article is written in English **Exclusion criteria** •If the research does not directly address extreme rainfall and/floods •If the article is based on systematic review or other synthesis methods (i.e. not original research) •If the paper does not have a DOI •If the paper's full text cannot be retrieved
Information sources	Nine CGIAR institutional data repositories
Search	As described in section 2.1
Study design	Climate research across all the CGIAR centers looking across all populations
Data collection process	Two-stage screening process based on inclusion and exclusion criteria:
Data extraction	1. TITLE/ABSTRACT •Screening within the Rayyan interface using titles/abstracts and removal of duplicates •Double screening of title/abstract (inclusion/exclusion criteria) to reconfirm the acceptability of each paper •Selection of articles considered relevant by AT LEAST one reviewer 2. FULL PAPERS •Download of full papers •Full paper double review (inclusion/exclusion criteria): •Papers selected by both reviewers – include Papers excluded by both reviewers – exclude •Discrepancies between two reviewers - a third reviewer will assessFull paper double reviewed (quality criteria) •Conduct topic modeling on the screened papers to identify climate and extreme rainfall and floods research topics conducted at CGIAR •Further screen by abstract to narrow down to papers on extreme rainfall and floods •Review each paper for insights on emerging trends on climate change-induced extreme rainfall/floods and their impact on agriculture and food security

the dataset in a way that makes sense. Through this process, we reconfirm the utility of OpenAI in analyzing and organizing large data-sets to generate useful research insights within a short space of time.

For the actual synthesis stage, we extracted from each paper information on first authors (e.g. name and country of affiliation), year, language, type of publication, study design, geographical location (e.g. region and country(ies)), subject of the paper, characteristics of the intervention, methods, impacts, policies or solutions). The review of the dataset was carried out in Excel using coding that facilitated quantitative analyses of the articles and interpretation of key insights from the included papers. To answer the key research questions, relevant text was extracted from each article in the dataset as datapoints for analysis. Through this process, key insights were extracted regarding the major sub-themes covered by CGIAR research on climate-induced extreme rainfall and floods, research methods used, impacts thereof, and potentially scalable solutions. Qualitative narratives emerging from this process tell a comprehensive story about the nature and impacts of climate-induced extreme rainfall on the agri-food sector and potential adaptation solutions.

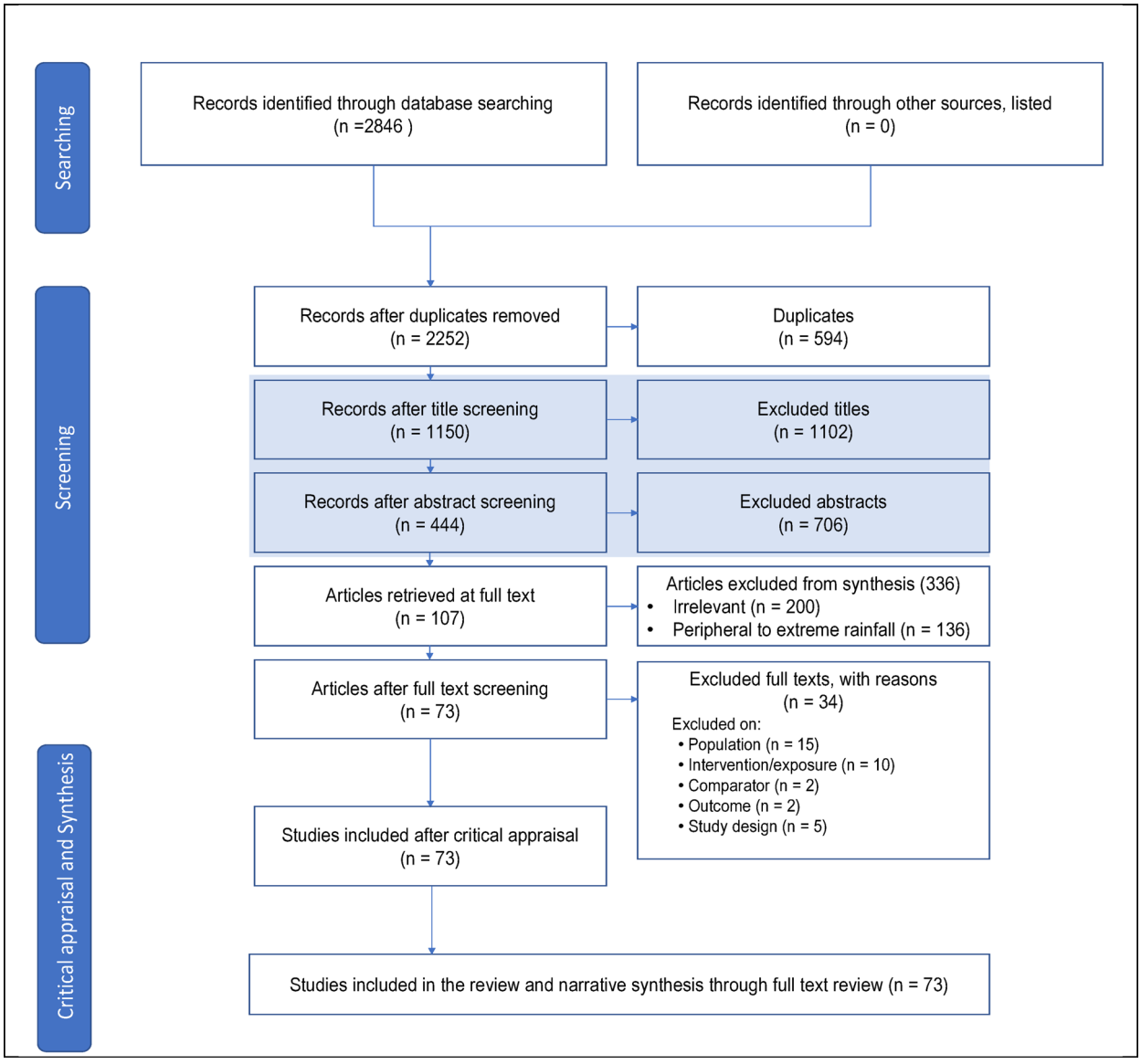


Fig. 2 ROSES flow diagram

Results of the study

Geographical distribution of the studies

In terms of regional distribution, the highest number of articles in the dataset (45) was based on research done in Asia, which constitutes 61.6% of the articles reviewed. This is followed by Africa with 24 articles (32.9%); and Latin America with 4 articles (5.5%). Figure 3 summarizes the regional distribution of the articles. Note that some of the articles cover research that was done in two or more countries or regions.

We also assessed the distribution of the studies by the countries where the research was done. We noted that some of the articles covered a whole region or river basin instead of specific countries. For example, there were 4 articles based on studies covering the Volta River Basin; 2 articles covered the Himalayas; 2 articles covered the Mekong River Basin; and 1 article covered the Amazon Delta.

On distribution by country of study, the results show that the highest number of articles were based on research done in Bangladesh (10 articles); India (9); and Nepal (8). In Africa, the highest number of articles was based on research done in Ethiopia (6); followed by Kenya (4). The results were not surprising because Bangladesh, India and Nepal are some of the countries in the world that frequently experience extreme rainfall and floods. Figure 4 shows the distribution of the studies by focal country.

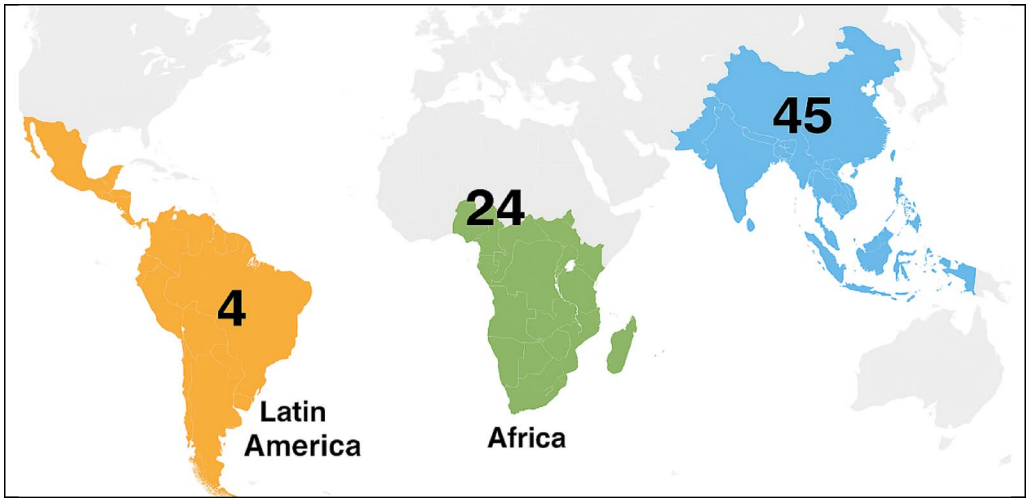


Fig. 3 Regional distribution of the articles reviewed

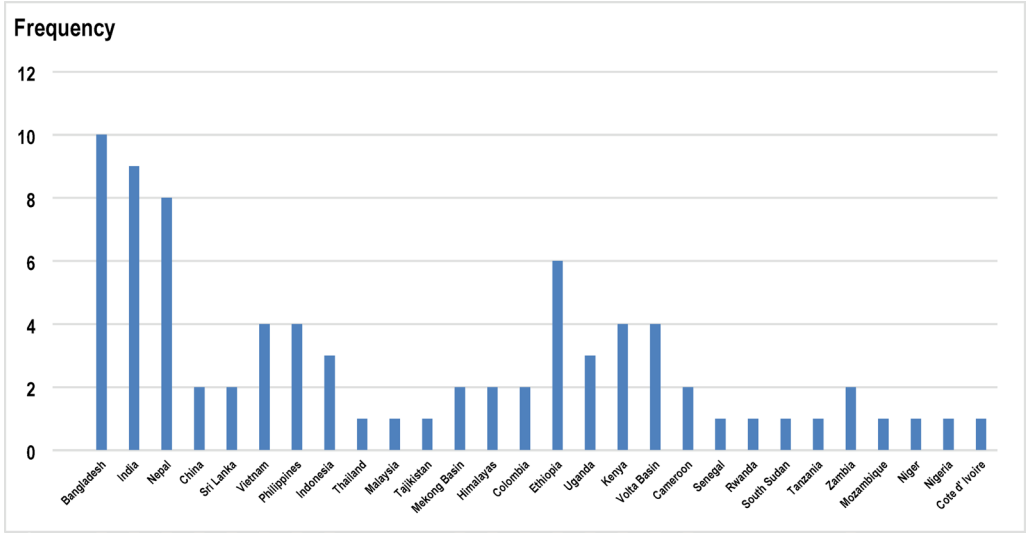


Fig. 4 Distribution of the studies by focal country

Main crops covered by the studies

The major crops covered by the dataset we reviewed include rice (6 papers); trees as part of agroforestry (5 papers); wheat (4 papers); and maize (3 papers). Rice, wheat and maize are staple crops in some of the countries where CGIAR conducts research. Other crops mentioned in the papers include cocoa, papaya, and beans [24, 61]. Most of the studies discuss these crops in the context of assessing crop losses due to impacts of extreme rainfall and floods in certain countries and localities or how certain adaptation options are suitable for specific types of crops. For example, the paper by Lasco et al., [44] presents results of smallholder farmer perceptions of climate change and the role of trees and agroforestry in climate risk adaptation in the Philippines. It concludes that "farmers had positive perceptions of tree roles in coping with climate change", with most timber tree species being "valued for excessive water regulating functions", while non-timber trees were valued as sources of food and income.

Distribution of the studies by cluster

There were several observable common themes that cut across most of the articles in the dataset. We describe these common themes according to the three clusters of interest for this review and relevant narratives are made for each of them to show the major insights emerging from the papers. In some cases, direct quotes are used to support the narratives. Note that there were some papers that addressed two or more sub-themes. For example, Aryal et al., [7] assessed the main climate risks and adaptation strategies of smallholder farmers in coastal Bangladesh and established that "cyclones, excessive rain and flooding, and salinity" were direct risks, while "crop

losses, diseases and pests" were a second layer of risks that the farmers face; Bastakoti et al., [11] examined perceived climate risks, their impacts, and existing adaptation practices at the local level in Vietnam and Thailand and concluded that the main perceived risks include "drought, floods, salinity intrusion, and crop losses". Therefore, adaptation practices must focus on these risks. However, the authors also highlighted that there is a critical "role for local institutions" in adaptation measures.

With regards to distribution of the papers reviewed across our main clusters of interest, see Fig. 5. There were more papers (37) that discussed the impacts of climate-induced extreme rainfall and floods. This constitutes 50.7% of the articles reviewed. This is followed by papers that discussed methods used by the CGIAR researchers to address climate-induced extreme rainfall and floods (35), constituting 48% of the articles reviewed. 34 articles covered solutions that have been tried out in different countries to adapt to the impacts of extreme rainfall and floods. This constitutes 46.6% of the articles reviewed.

We also noted that the majority of the articles in our dataset (56) used data from observations that have already been made in real life. This constitutes 76.7% of the articles in the dataset. 23 articles relied on projected data, especially using precipitation and temperature modeling techniques, while seven articles used both observed and projected data. This suggests that the majority of the researchers in our dataset used empirical data that closely resembles the actual lived realities of farmers and communities in the study sites.

Methods deployed by CGIAR researchers to study extreme precipitation

Researchers are often confronted by difficulties in selecting the most suitable research methods, tools, and techniques for studies on extreme rainfall. The technicality and complexity associated with the wide array of models and methods present additional challenges when it comes to their practical implementation in disaster applications [40]. It is no wonder that there has been a notable increase in the adoption of innovative models

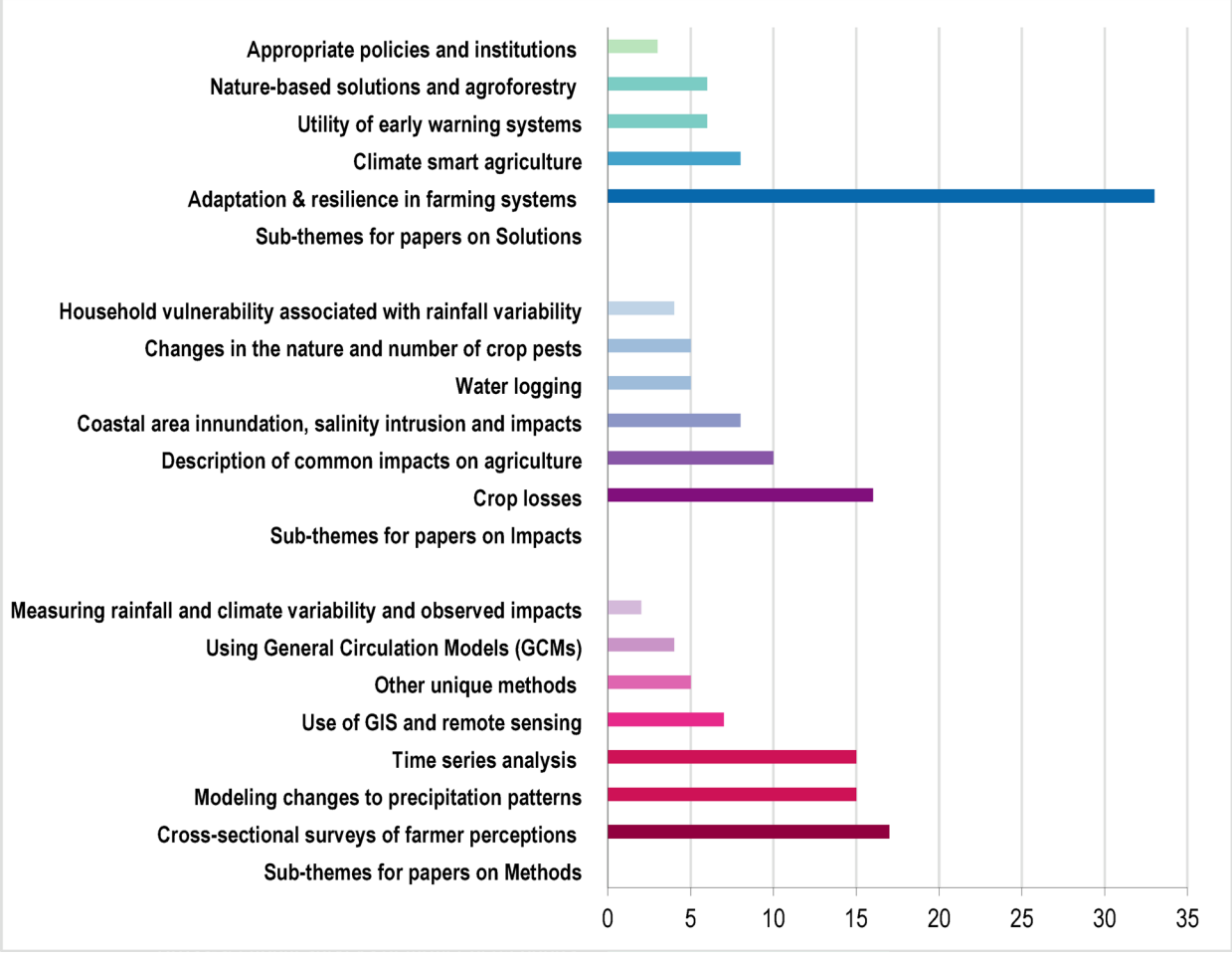


Fig. 5 Number of papers distributed across sub-themes of interest

and methods to address the challenges posed by climate change and natural disasters with the aim of building resilient and sustainable societies. These include climate modelling approaches at national, regional, atmospheric and earth systems levels [20, 47]. The diversity of methods for studying climate-induced extreme rainfall and floods is also reflected in our dataset.

Modelling and forecasting

In our dataset, we observed that 15 methods-related articles used a wide range of modeling and forecasting techniques to predict future changes in precipitation patterns and potential impacts. The results of the modeling done in most of the papers reveal that average annual and seasonal precipitation in the study sites in Asia and Africa is projected to increase up to at least 25% under various scenarios by year 2050. This suggests that the risk of floods is likely going to worsen and should therefore, be anticipated and planned for in countries that already experience extreme rainfall or floods [35, 62].

Mann-Kendall trend detection test

Among the articles that used modelling techniques, at least eight of them deployed the Mann-Kendall trend detection test to estimate changes in precipitation trends over specified time-periods to account for long-term persistence. Results of the modelling in most of the papers reviewed show that a significant increase in extreme rainfall is expected over the long-term as well as increased seasonal variability [4, 68]. For instance, Sa'adi et al., [58] carried out long-term trend analysis of extreme climate in the Sarawak tropical peatland of Malaysia using datasets that span 68-years (1948–2016) based on a Modified Mann-Kendall test. The analysis established that "a significant increase in extreme rainfall was expected during the Southwest monsoon compared to the Northeast monsoon". This suggests the need to prepare to mitigate and adapt to the impacts of extreme rainfall-related disasters in most of the study sites.

Historical time series analysis

At least 15 articles in our dataset used historical time series analysis of annual precipitation for different time durations to estimate the frequency of extreme rainfall events, projected changes in rainfall intensity in future, and to highlight emerging trends and fluctuations. The majority of the papers established that standardized annual rainfall anomalies revealed the spatial-temporal distribution of below and above normal rains that are associated with droughts and floods respectively. At the same time, general increases in annual precipitation are to be expected due to intensification of precipitation during the wet season in most of the focal countries. This suggests a potential increase in flood events during the wet season and increases the need for mitigation and adaptation measures in practice (see [42, 52, 70]).

Reanalysis techniques

At least 15 articles that used time-series analysis and forecasting models also used *reanalysis* techniques and observational datasets following the standard World Weather Attribution group protocol to generate a better understanding of trends in extreme rainfall and flood incidence [55]. Significant and insignificant wetting tendencies of the dry and wet seasons were respectively found to be consistent with rainfall alterations in most of the study sites and thus, influencing the frequency and intensity of extreme rainfall events [18, 33, 42].

Use of socio-economic surveys

At least 17 methods papers in our dataset relied on cross-sectional surveys that gathered stakeholder perceptions to understand the observed impacts of extreme rainfall and floods on crops and livelihoods and potentially scalable solutions that farmers and communities have already tried out. This constituted the biggest subset of articles on methods (23.3% of the dataset). Most of the findings of these studies converge around the fact that farmers are often influenced by factors such as farm management practices, knowledge of climate forecasts and the process of decision making for farming practices to mitigate or adapt to the impacts of climate-related extreme rainfall [21]. In addition, to enhance the adaptive capacity of households and local communities, there is need to "improve the technical capacity of farmers; create effective mechanisms for strengthening, promoting, and disseminating locally initiated efforts"; subsidize and improve access to credit services; as well as establishing effective mechanisms for coordination (Bastakoti, 2013).

Remote sensing and GIS

Seven papers under the methods cluster demonstrated the utility of high-resolution satellite images, GIS, and multi-decadal retrospective precipitation datasets to measure the magnitude of flood events that have occurred, the likelihood of extreme rainfall and floods in future, and the associated amounts of rain that may be expected to fall. The majority of the papers are able to demonstrate that earth observation, GIS and remote sensing are useful techniques whose untapped potential is vital for incorporation in research methods to help disaster managers deal with comprehensive flood condition analysis. This includes "swift, lucid and accurate decoding of flood inundation signatures" in specific river basins [50]. In some cases, these different but related tools have been used to analyze precipitation data and identify prime hotspots for flooding, which is crucial in planning for adaptation to the impacts of extreme rainfall and floods [60].

Climate modeling and GCMs

Four papers in our dataset used Global Circulation Models (GCMs) to estimate climate and extreme rainfall variability and changes over time in specific countries and regions. The deployed models are able to establish

changes in annual and seasonal stream flows and hydrological extremes such as droughts and floods. Most of the findings suggest that "current hydrological extremes are likely to increase in large parts of Asia, Latin America and Africa throughout the 21 st Century", with "the duration of high flows becoming longer compared to the current condition such that agri-food systems are severely impacted, and thus "calling for site-specific adaptation efforts" (Whitehead, et al., 2018 [39]; [31]). For instance, Ramirez-Villegas et al., [56] used 17 GCM outputs to quantify how Colombian agricultural production may be affected by climate change and estimate the expected changes from year 2040–2069. They conclude that "if no adaptation measures are taken, 80% of crops would be impacted in more than 60% of the current areas of cultivation", with particularly severe impacts in high value perennial and export crops. These findings are also consistent with the IPCC's Sixth Assessment Report which predicts that increased global warming will lead to more intense and frequent heavy rainfall events globally, except in some regions such as southwestern North America.

Unconventional research methods

Four papers in our dataset deployed what we considered as unique or unconventional research methods that were used to study extreme rainfall. These methods are widely varied and hence, their uniqueness. For example, Nguru et al., (2023) [53] utilizes satellite imagery, GIS mapping, and crop analysis to identify areas with high potential for flood residual water cultivation in Senegal. The study recommends the "integration of flood residual water cultivation with climate-smart agricultural management practices". This can aid in climate adaptation and economic empowerment in the studied regions, and in sub-Saharan Africa at large. A study by Guevara-Murua et al., [32] uses a 300-year hydrological variability dataset to demonstrate the potential for assessing societal impacts by analyzing Guatemala municipal council records to reconstruct the occurrence of floods over the period 1640–1945. The study established that "in total, 12 years of very wet conditions, 25 years of wetter than usual conditions, 34 years of drier conditions, and 21 years of very dry conditions were recorded" [32]. The study demonstrates that records of city and municipal council meetings can also provide a rich source of information for understanding extreme rainfall events.

Studies on impacts of extreme rainfall and floods

A large portion of the published literature agrees that agri-food systems bear much of the impact of extreme rainfall and floods, especially in developing countries that receive above average rainfall frequently. Agri-food systems absorb up to 80% of all direct impacts, with multiple effects on water availability, agricultural production, food security and rural livelihoods [45, 57]. Challenges faced in this terrain include loss of production, damage to agricultural infrastructure, and even psychological distress for the farmers [63]. The papers in our dataset articulate such impacts in various ways as outlined below.

Mapping of hazard, exposure and vulnerability

From the articles under the impacts cluster, there are at least 17 papers in which the researchers map the zones of extreme rainfall and floods, levels of exposure, affected communities/populations, levels of risk and vulnerability, and direct impacts on crops and other livelihood assets. In several cases, the articles that deal with impacts of extreme rainfall and floods generate documentary reports of the damage experienced in specific localities to provide insights on the scale of the impacts and what might be done to enable effective anticipatory action in future as well as adaptation [19]. Major vulnerability factors identified in the papers include access to food and water, social networks, natural disasters, and climatic variability. Flood, riverbank erosion, destruction of fishing camps, unemployment, and access to basic services emerge as major biophysical and socioeconomic factors determining livelihood vulnerability. At the same time, lack of finance and high costs tend to limit the ability of farmers to adopt improved technologies, suggesting an opportunity for policy and institutional interventions that support the farmers in a more meaningful way [2, 5, 12].

Waterlogging due to extreme rainfall

In our dataset, there were five papers that discussed waterlogging directly. Each of these papers invariably demonstrates how waterlogging results in substantial loss of crops and livelihoods if no interventions are made to adapt or mitigate these impacts. For example, Aryal et al. (2016) [6] explored whether a conservation agriculture-based wheat production system can better cope with climatic extremes than a conventional tillage-based wheat production system in Haryana, India, during periods with untimely extreme rainfall. The analysis showed that whilst "average wheat yield was greater under conservation agriculture than conventional tillage during both bad and normal years", the difference was two-fold greater during the bad years (16% versus 8%). This demonstrates that location-specific interventions are needed to reduce the impacts of waterlogging (Bastakoti, 2016) [10].

Impacts of coastal inundation and salinity intrusion

Eight papers in our dataset directly address coastal area inundation, salinity intrusion and observed severe impacts on crop production and livelihoods, especially in countries such as Bangladesh and Nepal. The results of the studies show that in years of average salinity intrusion and flooding, the crops would experience an average annual decrease when no climate-smart interventions are implemented; and when the flooding and salinity intrusion is above average, the crop losses also increase

exponentially. This suggests that there is a direct correlation between the extent of salinity intrusion and crop losses that should be understood and addressed in context [34, 48, 71].

Pests and diseases

Five papers in our dataset focus on changes in the nature and number of crop pests. For instance, Aryal et al., [7] studied risks posed by climatic variability and extreme weather events to smallholder farmers in coastal Bangladesh and concluded that "increased crop diseases/pests and livestock diseases were perceived as indirect risks resulting from climatic variability". The study by Ahmed et al., [2] assessed how climate risk perceptions and perceived yield loss increases agricultural technology adoption in the polder areas of Bangladesh. Findings of the study show that "farmers perceive polder agriculture as being highly vulnerable to flooding, drought, salinity, and pest infestation". Aryal et al., [8] investigated the main climate risks that farmers faced and the adaptation strategies they used in Bangladesh, Ethiopia, India, Kenya, and Nepal. They found out that among others, "excessive rainfall and heightened crop pest/disease incidence are commonly observed climate-induced risks in all study areas".

Studies on adaptation solutions

As the scale and intensity of climate-induced extreme weather events escalates, the need for adaptation solutions in agri-food systems becomes more pertinent. The IPCC (2019) points out that many practices can be optimized and scaled up to advance adaptation to extreme rainfall throughout the food system (*high confidence*); supply-side options include increased soil organic matter and erosion control, improved cropland, livestock, grazing land management, and genetic improvements for tolerance to heat and drought; diversification in the food system is a key strategy to reduce risks (*medium confidence*); demand-side adaptation, such as adoption of healthy and sustainable diets, in conjunction with reduction in food loss and waste, can contribute to adaptation through reduction in additional land area needed for food production and associated food system vulnerabilities. In this study, the reviewed articles show that the CGIAR has been researching and promoting the implementation of various adaptation solutions for extreme rainfall and flooding. These include climate-smart agriculture, flood-tolerant crop varieties, innovative water management techniques and early warning and decision support systems. Table 2 provides a summary of the main solutions promoted by CGIAR researchers as reflected in our data-set.

From the articles under the solutions cluster, the highest number of papers (33) discuss adaptation and resilience in smallholder farming systems that are routinely confronted by extreme rainfall and floods. Several of these papers link observed risks from extreme rainfall and floods in specific communities to farmers' coping strategies that experts could build on. For instance, the paper by [49] examines intensive and extensive adaptations to rice production in salinity-prone areas in Vietnam using a two-year panel dataset of 788 rice-growing households. The main adaptation strategies include construction of "salinity barrier infrastructure" and use of "larger rice field holdings". Bhatta & Aggarwal (2015) [13] studied adaptation options in Nepal, Bangladesh, and India, and concluded that across all study sites, the most frequently mentioned adaptive practices were "changing cropping patterns and adoption of flood resilient crop varieties". A large number of the farmers also placed

Table 2 Summary of main solutions promoted by CGIAR researchers

Solution category	Innovations	Innovation descriptor
(i) Innovative water management techniques	Alternate wetting and drying	An innovative water management system for rice paddies that intermittently drains fields thereby reducing water demand by up to 33%
	Improved irrigation efficiency	Promotion of advanced irrigation technologies and sound management practices to optimize water usage, particularly critical for water-intensive crops
(ii) Sustainable land & agronomic practices	Climate-smart agriculture	Promotion of techniques such as conservation tillage, agroforestry, and adjusted planting schedules. These boost productivity, reduce risk, and improve soil health
	Locally led adaptation and co-creation of solutions	Adaptation solutions are co-created with local communities to ensure cultural and economic relevance and foster community buy-in and sustainability
(iii) Appropriate policies and institutions	Developing climate-smart policies and institutions to support specific innovations	Working with national partners to develop frameworks, policies and institutions that support climate action, integrate local priorities into national planning, and improve decision-making processes for climate resilience
(iv) Climate-resilient crops	Breeding and introducing climate-resilient crop varieties	Development and deployment of new crop varieties for commodities such as rice, cassava and wheat that are tolerant to extreme rainfall. These help to assure food security even when the weather patterns become more unpredictable
(v) Climate information & financial services	Early warning systems (EWS)	Development and use of EWS for extreme rainfall and floods to provide farmers with timely, actionable information, reducing potential damage by up to 30%
	Risk contingent credit/insurance	Promoting crop risk insurance packages that provide loans where repayments are dependent on weather conditions and may be covered by insurance in the event of floods

emphasis on breeding crop varieties that tolerate adverse weather.

Climate-smart agriculture and crop production improvements

At least eight papers in our dataset assessed the link between climate-smart agriculture and crop production improvements in the face of extreme rainfall and floods. Among the variety of options arising therefrom, conservation agriculture-based crop production systems are observed as providing better coping mechanisms for extreme rainfall than conventional tillage-based crop production in different countries (Aryal at al., 2016) [6]. Another commonly deployed adaptation practice visible in the papers reviewed is the use of flood-tolerant crop varieties to improve crop yields and increase income. This is often combined with proper crop and nutrient management to optimize production [59]. Livelihood coping strategies for extreme events include storing food for consumption during years of poor crop yields, and diversifying sources of livelihoods and income [54].

Early warning systems

Of all disaster risk reduction and climate adaptation measures, early warning and anticipatory action are among the most proven and cost-effective ways to save lives and reduce losses (UNDRR, 2025) [69]. There are six papers in our dataset that address the utility of early warning systems in adaption to the impacts of extreme rainfall and floods. The early warning systems provide farmers and communities the opportunity to improve their seasonal disaster preparedness. For example, Koppa and Amarnath [41] assessed how farmers apply climate forecast information to manage rice cropping systems in Indonesia. Results showed that farmers were influenced by factors such as "knowledge of climate forecasts and the process of decision making for farming practices with regard to the use of climate forecast information. In addition to improve the forecasting of climate change and floods, "stakeholder-driven processes are needed that allow two-way communication between forecast issuing institutions, famers organizations and farming communities" [24]. In Sri Lanka, the International Water Management Institute established a platform that provides early warning information about climate disasters such as floods, landslides and droughts, with inputs from space-based information and nationally triggered datasets for early warning mechanisms.

Nature based solutions and agroforestry

At least six papers in our dataset focus on deployment of nature-based solutions and agroforestry as a viable intervention for addressing waterlogging and improving crop production. For instance, the study by Simelton et al., [61] examined the suitability and role of trees and agroforestry in coping with extreme rainfall events in Vietnam. They established that trees were very useful as a buffer against floods such that those "farms with trees had shorter recovery time after most types of natural disasters" when compared to farms without trees. Evaristе et al., (2018) [23] analyzed climate change vulnerability and local adaptation strategies based on community perceptions and biophysical evidence in Cameroon. They concluded that "mangrove reforestation and the development of sustainable supply chains for wood fuel" are some of the main pathways for adaptation planning in the study sites.

Importance of supportive policies and institutions

At least three papers in our dataset discuss the primacy of appropriate policies and institutions as necessary ingredients for adaptation to the negative impacts of extreme rainfall and floods. These papers tend to analyze the strengths and gaps in national policies and institutions to generate more insights on capacity strengthening interventions for smallholder farmers. They recommend the design and deployment of policies and institutions that are fit-for-purpose as one of the key ingredients for successful adaptation [14]. For example, Tall et al., [65] examined the heterogeneity that exists within Africa's institutional arrangements for climate-related disaster risk management and introduces a policy classification framework that ranks each country as one of three disaster management policy types. They established that "African countries lay at different levels on the spectrum of effective disaster risk management" as per the Hyogo Framework of Action. This suggests that there is need for a "concomitant heterogeneity in aid programs and initiatives" targeted at strengthening disaster risk reduction and adaptation efforts in Africa.

Strengths and weaknesses of the identified solutions

While most of the identified solutions have their merits that were determined through field trials and testing, they also have their own weaknesses. We carried out a brief analysis to systematically demonstrate the strengths, weaknesses, opportunities, and threats (SWOT) related to the adaptation solutions articulated by the CGIAR researchers. Insights from the articles in our data set reveals several strengths, weaknesses, opportunities and threats to the solutions proposed for addressing extreme rainfall as summarized in Table 3.

We also assessed the evident disjuncture between the ideal situation and current realities on the ground in terms of support for smallholder farmer adaptation. Table 4 presents a summary of the results of our assessment.

Table 3 SWOT Analysis for CGIAR adaptation solutions

Strengths	Weaknesses
• Generating multiple benefits beyond adaptation to extreme rainfall/floods: for instance, in addition to flood control, nature-based solutions were found to generate other benefits such as improved water quality, enhanced biodiversity and social well-being • Improving resilience and adaptability: climate-smart solutions such as draining of floodplains were determined to be often more flexible and adaptable to changing climate conditions and future uncertainties when compared to conventional grey infrastructure that can easily fail because of being locked into certain design standards • Long term cost-effectiveness: even though capital costs for design and implementation could be steep, many climate-smart approaches for addressing extreme rainfall were determined to have lower maintenance and operational costs in the long term compared to mainstream hard engineering solutions • Early warning systems lead to direct improvements in data generation and monitoring, thereby providing more useful insights for planning and real-time response to extreme rainfall events	• Climate-smart solutions for extreme rainfall such as flood protection systems require high capital investment and may cause financial constraints for the farmers. • Data and knowledge gaps: lack of reliable, location-specific data and climate projections are weaknesses associated with the implementation of adaptation solutions • In some cases, fragmented institutional coordination between different agencies in sectors such as water management and economic development planning, and weak implementation and enforcement of policies impede the effective deployment of solutions • There are uncertainties about the efficacy of climate-smart solutions during extreme, high-magnitude flood events compared to traditional hard infrastructure • Increased variability and unpredictability in rainfall patterns makes it difficult to design systems with appropriate long-term standards • Implementation of solutions may involve difficult social trade-offs such as the opportunity costs of not developing floodplains or the displacement of communities for restoration projects. A lack of meaningful community engagement and potential conflict of interest among various stakeholders can lead to resistance and lack of local buy-in
Opportunities	**Threats**
• Climate-smart solutions for extreme rainfall present significant economic opportunities in the form of new markets for innovative technologies, job creation in planning, construction, and maintenance of flood adaptation infrastructure, and long-term cost savings from reductions in disaster damages • The search for solutions can create opportunities associated with the development and implementation of high-tech solutions for agri-food systems. EWS enable the deployment of real-time monitoring satellite systems for real-time flood tracking with greater accuracy • Opportunities arise for the development of advanced stormwater management solutions, including smart drainage systems that use AI to steer water to less sensitive areas • The insurance industries have an opportunity to innovate through the development of insurance packages that are tailored to the needs of smallholder farmers such as parametric insurance • In cases where nature-based solutions are the preferred option, they provide additional benefits that enhance local welfare, such as improved air and water quality, groundwater recharge, restored wildlife habitats, and new recreational opportunities, which can attract talent and businesses to urban centers • Investing in climate-smart solutions promotes long-term economic stability and community resilience, helping communities recover faster and "bounce back better" from extreme rainfall related disasters	• Knowledge gaps and data scarcity present serious challenges. There is often a lack of sufficient long-term, high-resolution data on local climate patterns, precipitation intensity, and river flow, particularly in developing regions. This scarcity makes it difficult to accurately model future flood risks and the performance of nature-based solutions under extreme conditions. While the CGIAR has done a lot to close this gap, it remains a matter of concern in the focal countries • Modeling limitations: current climate models and flood forecasting tools may not have the spatial and temporal resolution needed to predict localized, short-duration extreme rainfall events accurately, which are the primary cause of flash floods in many countries • The effectiveness of some climate-smart solutions, particularly nature-based ones, under future, more extreme storm conditions remains an area of active research with limited validation data from real-world events • High upfront costs remain a major threat for poor smallholder farmers. Many climate-smart solutions, while potentially offering long-term benefits, require substantial initial investment, which can be a significant barrier for local governments and smallholder farmers • Policy gaps and inconsistencies: existing policies may not fully integrate climate change projections or the use of NBS, leading to "business-as-usual" planning that exacerbates future risks • Equity and vulnerability: adaptation measures might disproportionately affect vulnerable communities, for example, through forced displacement or if the performance of solutions varies in socially disadvantaged areas

Discussion

We set out to review and understand CGIAR's contributions to climate change adaptation research and scholarship between 2012 and 2023 in the context of extreme rainfall and floods. Thus, we analyzed the evidence base, methodologies, and types of knowledge produced, disseminated or implemented. We also wanted to examine the geographical distribution and thematic representation of CGIAR's research outputs, identifying underrepresented regions and research themes that might require further attention. This includes highlighting major areas of focus, emerging trends, more recent developments, methodologies and concepts applied when addressing climate-induced extreme rainfall and floods, the impacts thereof, vulnerability of communities, and potentially scalable adaptation solutions.

From the analysis, it is apparent that CGIAR scholarship in this dataset is based on research that was concentrated in Southeast Asia and Africa, with more studies having been conducted in Bangladesh, Nepal, and India than anywhere else. This makes sense given that these are countries that are historically more prone to extreme

Table 4 Comparative policy gap assessment on reactive vs. anticipatory actions

Policy issue	Current reactive policies	Proposed anticipatory actions	Identified policy gaps
Financing anticipatory action for adaptation to climate change	- Funding released *after* floods occur (disaster relief funds) - Slow disbursement and bureaucratic triggers - Focus on compensation & social protection rather than prevention and adaptation	- Anticipatory finance mechanisms triggered by forecasts (e.g., parametric insurance) - Smallholder farmer-friendly micro-credit - Pre-positioned budgets for early action - Climate-risk stress testing for national budgets	- Lack of forecast-based triggers for anticipatory finance - Limited access to micro-credit for smallholder farmers - No institutional framework for proactive disbursement - Limited integration of climate-risk scenarios into national financial planning
Climate risk management & early warning	- EWS exist but only for meteorological alerts, with weak link to actionable response - Siloed hydrology–meteorology operations	- Integrated hydro-climate early warning with tiered response protocols at national and local levels - Multi-hazard warning systems linked directly to anticipatory actions	- Weak institutional coordination - Alerts not tied to funding or mandatory preparedness actions
Community preparedness & capacity building	- Training delivered only after crises - Community plans not regularly updated - Limited technical capacity at local level	- Capacity-building mandates for local governments and communities - Regular simulation exercises tied to risk forecasts - Promotion of locally suitable and appropriate climate adaptation innovations	- No sustained, funded training programs - Capacity building neither institutionalized nor mandatory
Data, knowledge & research integration	- Limited integration of climate projections into relevant sectoral policies - Lack of structured research uptake initiatives	- Continuous climate-risk intelligence systems - National platforms for science–policy-practice dialogue and co-production - Integration of indigenous knowledge into research & policy analysis	- Limited translation of research into policy & practice - Limited use of indigenous knowledge in research & policy analysis

rainfall events and floods than other countries. It also means that the results cannot be generalized because the research itself was quite context-specific. In terms of crop representation, rice and wheat dominate the scholarship reviewed. This is not surprising given that these are water-intensive crops that may thrive better in contexts of extreme rainfall when compared to other crops. Maize also features prominently in the dataset, especially in African study sites where it is a staple crop in many countries. The use of nature-based solutions such as planting trees as a buffer for waterlogging is also reported in several articles reviewed, especially those based on research done in Southeast Asia. With regards to major areas of focus and emerging trends, papers in the dataset were almost equally-distributed across the three analytical clusters of methods, impacts, and solutions, each with 35, 37, and 34 articles respectively. This implies that CGIAR research has paid relatively equal attention to all the three clusters.

With regards to the main areas of focus reflected in our dataset, nuanced analysis shows that from the methods cluster, there were more articles based on research that used cross-sectional surveys of farmer perceptions on the impacts of extreme rainfall/floods, adaptation measures and solutions that they have deployed to-date. Other frequently deployed methods reflected in the dataset include use of modeling and forecasting techniques and time-series analysis to establish the patterns of extreme rainfall and/floods, potential impacts thereof and subsequent prediction of extreme rainfall events in future. From the impacts cluster, there were more articles based on research that described in detail the physical loss of crops due to extreme rainfall events and floods. Other themes that stand out under the impacts cluster include detailed description of coastal area inundation, salinity intrusion, and the impacts experienced in various countries.

From the solutions cluster, there were more articles based on research that focused on adaptation options and resilience of smallholder farming systems. Most of the insights were generated from farmers' description of the challenges they face and how they have adapted and/mitigated those challenges over time. Other themes that stand out include the utility of early warning systems in adaptation processes; and how climate-smart agricultural technologies such as conservation agriculture, flood-resilient seed varieties, and agroforestry may be deployed to enhance crop production. The insights from the dataset also show that while farmers in different countries have been trying out various adaptation options, lack of finance and knowledge tends to limit their ability to adopt improved technologies and innovations, suggesting the need for more supportive policies and institutions that enable access to credit and other friendly financial packages for the smallholder farmers. For farmers' knowledge limitations, capacity building interventions are presented as a counter measure that researchers and practitioners in the sector should leverage.

In our dataset, there is comparatively a larger number of studies done in Asia than in Africa and Latin America,

which suggests that CGIAR research might be generally excluding some countries that are already known to be prone to extreme rainfall events and floods such as Mozambique and Madagascar. This indicates a critical research gap that might need to be addressed from a geographical distribution standpoint. There is also absence of scholarship addressing important themes such as the impacts of extreme rainfall on roots and tubers, fish, and livestock; utility of flood insurance for crops; and promotion of urban and peri-urban agricultural systems. Only one paper in the dataset quantifies the economic losses and damages from floods and extreme rainfall. Also missing from the dataset are attribution studies that explore the link between extreme rainfall and climate change.

In terms of research on crops, there is more focus on rice and wheat in the dataset even though other crops are also usually damaged when extreme rainfall events occur. All these are further areas of research focus that the CGIAR might have to consider in the near future when addressing climate-induced extreme rainfall and floods. We are, however, encouraged by the frequent deployment of stakeholder participation approaches in the identification of solutions by the CGIAR researchers because these approaches are known to enable the design and promotion of practical human-centered interventions that stand a higher chance of success at the implementation stage. Therefore, efforts in that direction should be continued.

Recommendations for smallholder farming policy and practice

Our analysis reveals that there are some viable entry-points for upscaling impactful interventions documented by CGIAR researchers in countries affected by extreme rainfall and floods. The main impacts of extreme rainfall addressed by the CGIAR include physical loss of crops due to coastal area inundation, waterlogging, and salinity intrusion. Therefore, policy and strategic interventions for farmer adaptation to the impacts of extreme rainfall should ideally target these impacts. Several adaptation options that can build the resilience of smallholder farming systems are observable from the study.

More specifically, the concentration of CGIAR research in South East Asia suggests the need to expand the consortium's geographical area coverage to other countries in Africa and Latin America where research is likely to be needed. In this regard, financial resources would need to be mobilized to support research in underrepresented countries such as Mozambique, Madagascar, and other flood-prone countries in Africa and Latin America, thereby generating more globally representative evidence. Current CGIAR research centres in Africa and Latin America are well-positioned to support this expansion so that strategies for adaptation to extreme rainfall impacts are implemented that are tailored to different contexts beyond Southeast Asia.

Analysis of the data set also enabled the identification of research gaps that may call for the broadening of thematic areas of focus in CGIAR adaptation research on extreme rainfall and floods. In this regard, it would be helpful to promote research on more diverse cropping systems, including roots and tubers, livestock, fish, and urban/peri-urban agriculture, which are currently underexplored by the CGIAR despite their well-known economic and nutritional benefits. It would also be important to integrate attribution studies that help in improving knowledge on the direct links between extreme rainfall and climate change, thereby informing the targeted interventions arising from CGIAR research. Studies that specifically quantify economic losses from floods are also encouraged as they could generate important insights for more effective support to public policy formulation, agricultural investment, and risk management.

Most of the research done by the CGIAR focuses on strengthening support for smallholder farmer agricultural production. Insights from the reviewed articles suggest the need to develop more inclusive smallholder financing packages and/mechanisms such as microcredit, low-interest loans, or climate risk insurance schemes to support adoption of climate-smart technologies. Crop and flood insurance schemes tailored for smallholder farmers are highly likely to help in building their resilience against shocks from extreme rainfall events. The possibility of public–private partnerships to fund and sustain adaptation programs among vulnerable rural communities should also be explored to widen sources of funding. All these options would help in addressing the financing challenges that smallholder farmers face in CGIAR study locations. The payoff for investing in these innovations is high, with analyses showing that every dollar spent on agricultural research by the CGIAR and other institutions yields about $10 in benefits for farming communities through higher yields, better nutrition and reduced crop losses [17].

More importantly, these efforts save lives and livelihoods by helping farmers adapt rather than abandon their way of life, which suggests the need to strengthen local institutional capacity to plan for climate risks, involving women, girls and marginalized groups in decision-making, and aligning with government policies so that successful pilot interventions can scale up to large programs (ibid.). It is evident that smallholder farming communities covered by our data set also face significant technical and financial capacity gaps. Therefore, CGIAR Centres and their program implementing partners such as civil society organizations and government departments should design and implement robust

capacity-building programs that address identified smallholder farmer knowledge gaps on the deployment of climate-smart agricultural practices, early warning systems, and nature-based solutions. This could be complemented by promotion of well-structured financing mechanisms and community-based adaptation strategies that leverage farmers' indigenous knowledge systems alongside the scientific innovations that CGIAR researchers develop or identify.

Several solutions are profiled in the data set that we analyzed and these provide important pointers for policy and practice. For instance, the promotion of climate-smart agricultural practices seems to be one of the non-negotiable pillars of adaptation to extreme rainfall and floods. This includes prioritizing the scaling up of proven adaptation solutions such as flood-resilient seed varieties for rice, wheat, and maize; conservation agricultural practices; agroforestry and buffer tree planting to reduce waterlogging; and advanced early warning systems for flood and rainfall forecasting. Indeed, a people-centred approach to the deployment of early-warning systems for flooding can help minimize the harm to crops, people, assets, and livelihoods by triggering early action that has been tried and tested. It is important too also note that some of these potential solutions would be easier to scale up if they are integrated in national climate change adaptation plans.

For the adaptation solutions to work more effectively in practice, it is also vital to enhance CGIAR methodological innovation and integration. This implies that the CGIAR consortium should invest more in modeling and forecasting tools that can be used to strengthen early warning systems and community level disaster-preparedness capacities. It is apparent that the CGIAR already deploys interdisciplinary approaches that combine physical, economic, and institutionalized participatory approaches to produce social data necessary for designing various adaptation solutions. Efforts in that direction should be strengthened and continued. This includes fostering broader stakeholder engagement and natural resource governance approaches in adaptation planning, and ensuring that smallholder farmers, local communities, and civil society play a central role in decision-making. In addition, it is crucial to strengthen the nexus of agri-food policy making, research, and practice to enable study findings to directly inform climate adaptation policies, agricultural extension, and disaster risk management frameworks. Overall, directing more investments towards flood-resilient seeds and other climate-smart agricultural innovations will be crucial for adapting to the impacts of extreme rainfall and floods in the smallholder agri-food systems in CGIAR focal countries.

Study limitations and future research

This study was delimited to CGIAR research done between 2012 and 2023. It is highly likely that newer research done from 2024 to 2025 could also be quite insightful. Since this was not a wide-ranging systematic review of global literature, articles published by researchers outside the CGIAR system were excluded and yet this wider scholarship could have added value to the understanding of research methods, impacts, and solutions associated with climate-induced extreme rainfall and floods. The distribution of the studies in the data set was skewed towards South East Asia as well as rice, wheat and maize; there were very few studies done in Latin America. This limits the generalizability of the findings.

In addition, our dataset was compiled using "climate change" as the main search term for title, abstract and keywords. If the terms "flood" and "extreme rainfall" were used without any reference to climate change, many relevant studies would not be identified. Since all the authors are fluent only in English, studies published in other languages such as French and Portuguese were excluded. Thus, key insights from non-English articles were missed. We also limited ourselves to journal articles published by the CGIAR researchers, which excludes insights from book chapters, blogs and other forms of grey literature that would still have important insights. Despite these limitations, we are convinced that we still managed to get a relatively good overview of the CGIAR research on climate-induced extreme rainfall and floods given the large number of papers in our dataset and their diversity across different thematic areas of importance.

Supplementary information

Original data set https://docs.google.com/spreadsheets/d/1Gl21ORIGINAL_DATASET.
Coded data set https://docs.google.com/spreadsheets/d/CODEBOOK.

Table 5 Summary of the impacts of extreme rainfall on agri-food systems

Variable	Direct impacts	Indirect impacts
On-farm agricultural production	• **Crop Damage & Loss**: Waterlogging, root suffocation, and physical damage to crops • **Soil Erosion & Nutrient Loss**: Heavy rainfall washes away topsoil, reducing soil fertility • **Soil Waterlogging & Oxygen Deprivation**: Limits root respiration, stunting growth • **Pest & Disease Outbreaks**: Increased humidity fosters fungal infections, pests, and vector-borne diseases • **Livestock Mortality & Morbidity**: Drowning, hypothermia, disease outbreaks (e.g., foot-and-mouth disease) • **Infrastructure Damage**: Destruction of irrigation systems, greenhouses, farm roads, and drainage structures • **Seed Loss & Reduced Germination**: Seeds washed away or failing to sprout due to excess moisture	• **Reduced Future Yields**: Long-term soil degradation affects future productivity • **Delayed Planting & Harvesting**: Flooded fields delay crop cycles • **Changes in Cropping Patterns**: Farmers may shift to flood-resistant varieties or alternative crops • **Increased Production Costs**: Need for replanting, pest control, and soil restoration
Post-Harvest Handling & Storage	• **Post-Harvest Losses**: Floodwater damages harvested crops, stored grains, and perishable goods • **Contamination of Food Stocks**: Floodwaters introduce pathogens, mold, and toxic substances like aflatoxins • **Storage Infrastructure Damage**: Warehouses, silos, and cold storage units get submerged or structurally weakened • **Transportation Disruptions**: Washed-out roads and bridges delay the movement of goods	• **Increased Storage Costs**: Need for emergency drying, fumigation, or relocation of food stocks • **Quality Deterioration**: Water exposure reduces the market value of crops • **Market Supply Volatility**: Inconsistent food availability affects price stability
Processing & Distribution	• **Damage to Processing Facilities**: Flooded factories, damaged machinery, and supply chain breakdowns • **Loss of Raw Materials**: Disrupted farm-to-factory supply reduces processing efficiency • **Energy & Water Supply Interruptions**: Power outages and water contamination affect food processing	• **Higher Processing Costs**: Increased need for repairs, alternative supply sources, and energy backups • **Shift in Market Demand**: Processors may struggle to secure raw materials or face new demand patterns • **Disruptions to Export & Import**: Flood-affected areas may face trade restrictions or delays
Retail & Market Access	• **Damage to Markets & Shops**: Flooding disrupts wholesale and retail networks • **Loss of Perishable Goods**: Fruits, vegetables, dairy, and meat spoil due to delayed transportation or power cuts • **Supply Chain Interruptions**: Road closures, logistical delays, and workforce displacement	• **Price Volatility & Inflation**: Reduced supply drives up food prices • **Reduced Consumer Access**: Flood-affected populations may face food shortages • **Shifts in Consumer Preferences**: People may opt for flood-resistant or non-perishable foods
Food Safety & Consumption	• **Waterborne Contaminants in Food**: Floods introduce bacteria (E. coli, Salmonella), heavy metals, and toxins into food systems • **Increased Risk of Foodborne Diseases**: Poor sanitation leads to outbreaks of cholera, diarrhea, and typhoid • **Loss of Nutrition Security**: Damage to nutrient-rich crops (e.g., fruits, vegetables) reduces dietary diversity	• **Malnutrition & Health Crises**: Food shortages and price hikes exacerbate undernutrition and hunger • **Higher Household Expenditures on Food**: Families spend more on food, reducing resources for other necessities • **Disruptions to School Feeding & Public Food Programs**: Flood-damaged infrastructure affects food assistance programs
Broader Systemic Impacts	• **Damage to Rural Livelihoods**: Smallholder farmers and agribusinesses face financial ruin • **Displacement of Farming Communities**: Flood-affected populations may be forced to migrate	• **Shifts in Agricultural Policy & Investment**: Governments may redirect funds to flood relief rather than long-term agricultural development • **Changes in Global Food Trade**: Countries reliant on flood-hit regions may need to seek alternative suppliers • **Increased Pressure on Social Safety Nets**: Greater reliance on food aid and emergency relief programs

Source: Authors' understanding of impacts of extreme rainfall on agri-food systems

Annex 1

See Table 5.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40066-026-00640-w.

Supplementary Material 1

Supplementary Material 2

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Author contributions
Design of study methodology, article screening, data analysis and visualization, manuscript writing, review and editing, data curation – C. C.- Study conceptualization, funding acquisition, design of study methodology, manuscript review and editing, quality control, and supervision – M. A.- Project administration, data visualization, manuscript review and editing – B. C.- Article screening, manuscript review and editing – K. K. and M. R.

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Data availability
All data generated and analysed during this study is included in this published article and its supplementary information files.

Declarations

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Competing interests
The authors declare no competing interests.

Author details
[1]Africa Centre for Resilience & Innovation, Cape Town, South Africa
[2]International Livestock Research Institute, Nairobi, Kenya
[3]Environmental Sciences & Management Unit, North West University, Potchefstroom, South Africa
[4]Council for Scientific and Industrial Research, Pretoria, South Africa

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