Sustainable Futures 10 (2025) 101459

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Impact of climate change on Ethiopian Arabica coffee production and current challenges it poses to coffee value chain

Guta Regasa Megerssa [a,*], Weyessa Garedew [a], Kristjan Jespersen [b], Janina Grabs [c], Adugna Eneyew Bekele [a]

[a] Jimma University, College of Agriculture and Veterinary Medicine, Ethiopia
[b] Department of Management, Society and Communication, Copenhagen Business School, Denmark
[c] University of Basel, Basel, Switzerland

ARTICLE INFO

Keywords:
Coffee shifting
Deforestation
Frost
Khat cultivation
Landslide
Land tenure

ABSTRACT

Ethiopia's coffee sector, pivotal to the nation's economy and cultural identity, is currently navigating a labyrinth of natural factors with climate change casting a long and formidable shadow over the future. This necessitates various measures to improve coffee sector resilience through the use of sustainable agricultural techniques. Accordingly, this study aimed to examine the effects of climate change on Arabica coffee production and the challenges it poses to the coffee value chain. This study used a mixed approach that combined both qualitative and quantitative research methods. Data were collected from 1020 coffee producers through a survey, 30 focus group discussions, and 67 semi-structured interviews. The findings show that climate change affects Arabica coffee by increasing temperature, changing rainfall patterns, and extreme weather occurrences, leading to disease proliferation, post-harvest loss, shifting suitable coffee areas, and expansion of khat and commercial trees. Generally, the current impact of climate change on the coffee value chain underscores the immediate need for policymakers and agricultural practitioners to effectively implement sustainable coffee production, processing, storage, and transport methods to enhance the sector's resilience.

1. Introduction

Climate change is gaining worldwide attention, emphasizing the urgent need for global action to mitigate its effects [1]. The impact of climate change poses significant social and economic challenges, especially for those reliant on natural resources [1,2]. Climate change affects the social, economic, and environmental sustainability through various related variables. For example, climate change contributes to extreme weather occurrences [3–5], such as floods, droughts, storms, waterlogging, frosts, snow, and severe rainfall, which cause significant damage and disruptions [3,5–7]. These events are aggravated, especially when temperature and precipitation exceed a certain threshold [8,9]. These natural catastrophes have a profound impact on human, environmental, and biological resources [10–12]. Their effects extend to various industries, organizations, and economies [13]. The agricultural sector is particularly exposed to extreme climatic occurrences [14–17]. They contribute to decreased productivity, lower incomes, higher price volatility, and food insecurity [2,5,18,19]. Besides, climate extremes can exacerbate the proliferation of diseases and insect pests [2,3,20–23]. Their cumulative effects can cause resource depletion, displacement, social tensions, reduced yields, increased food insecurity, and expose farmers to shocks and poverty [6,16,24,25]. It is anticipated that the impact of these extreme weather events will become more frequent and severe in the coming decades, necessitating global responses [3].

Developing countries are more vulnerable to climate change; however, their efforts to mitigate climate change are still minimal [26]. The agriculture sector is one major area where the profound impact of climate change occurs in these nations. Climate variables, such as rainfall and temperature variations affect agricultural production, production suitability areas, and rural livelihoods [27]. Climate change also induces disease and pest outbreaks, which significantly affect agricultural productivity [28]. Smallholder farmers who lack modern agricultural technologies are particularly vulnerable to climate change [29–31]. Climate change threatens smallholder farmers by potentially reducing crop yields, increasing production costs, exacerbating poverty, and disrupting ecosystems [29,32–34].

* Corresponding author.
E-mail addresses: jiineguta2014@gmail.com, guta.regasa@ju.edu.et (G.R. Megerssa).

https://doi.org/10.1016/j.sftr.2025.101459
Received 12 February 2025; Received in revised form 7 October 2025; Accepted 18 October 2025
Available online 2 November 2025

Arabica coffee is highly sensitive to climate change [35,36]. Climate affects coffee production by changing the temperature and rainfall patterns in coffee-growing regions [37–39]. However, the Ethiopian coffee sector is very important for the economic development of the country [40,41]. Despite its multifaceted contributions, the coffee sector faces several challenges that impede its optimal growth trajectory [42, 43]. Natural calamities exacerbated by climate change pose substantial threats to both production and marketing endeavours [39,44–47]. The impact causes the loss of Arabica coffee, which has significant social, economic, and ecological implications [48]. Climate change thrusts coffee producers into a cycle of uncertainty by reducing coffee yields and household incomes, precipitating a cascade of negative outcomes including food insecurity and entrenched poverty [49–52]. The effects further cause reduction in coffee quality, income, and export earnings, leading to economic contraction [53–55]. However, promoting climate-resilient practices such as tree shade management, soil and water conservation, improved coffee varieties, agroforestry, irrigation, and diversifications can enhance economic retention in the coffee sector [56–60]. These measures will also ensure sustainable coffee production and marketing, thereby attracting more investment for economic growth. Therefore, this research aims to study the impact of climate change on Ethiopian Arabica coffee production and the current challenges it poses to the coffee value chain.

Arabica coffee, with its limited genetic diversity, is deemed ecologically appropriate at latitudes ranging from 20°N to 25°S and elevations ranging from 700 m to 2000 m above sea level [52]. This geographic specificity is attributed to the genetic diversity of Arabica coffee, which necessitates cultivation within narrowly defined biophysical and climatic parameters [61]. Coffee suitability is likely decreasing overall due to rising temperatures and precipitation patterns [38,44,45,62,63]. This may force coffee production to move to higher altitudes or latitudes; however, this would not always ensure significant benefits [48,63,64]. Hence, digitally supported agricultural production technology has the potential to significantly enhance resource utilization and total yield [65]. There have been increasing concerns regarding the future quantity and quality of coffee yields [66]. Climate change further disrupts the supply of raw materials, transportation, and logistics [67–70]. This shows that the intricate nexus between natural forces, institutional dynamics, and global market influence underscores the imperative for concerted efforts to address the multifaceted challenges confronting Ethiopia's coffee sectors, necessitating holistic interventions that bridge ecological resilience, institutional capacity, and economic sustainability. This research, therefore, underscores the necessity of understanding the impact of climate change on coffee value chains to improve Arabica coffee' resilience and ensure its long-term production.

This research seeks to unravel a critical inquiry: How does climate change affect Ethiopian Arabica coffee production and what challenges do it currently pose to the coffee value chain? This research can help policymakers better understand the challenges of climate change, particularly the impact of extreme weather events, consequences of agroecological coffee suitability changes, khat and commercial tree expansions, and the development of more robust resilience measures to increase support for the Ethiopian coffee industry. It is also expected to serve as an alert, prompting decision makers to take preemptive actions to protect coffee-suitable environments, particularly in highland regions. Furthermore, this study provides academic insights into how climate change affects the coffee industry in various ways, with the potential to disrupt the global coffee value chain. This study is anticipated to serve as a ladder for academics to conduct further research beyond coffee farms.

2. The Ethiopian coffee value chain

Ethiopia is the birthplace of Arabica coffee. The country is the top African coffee producer and the fifth-largest coffee exporter worldwide [71,72]. Coffee contributes to the country's exports and total foreign exchange earnings, accounting for over 50 % and 25 %, respectively [73, 74]. Half of the total coffee production remains in the domestic market for consumption, which also distinguishes it from other coffee-producing countries. Moreover, having a unique flavor makes the Ethiopian Arabica coffee more popular in the specialty coffee market. There are four coffee production system in Ethiopia; forest coffee, semi-forest coffee, garden coffee and plantation coffee [39,43,75]. Smallholder farmers participate in the former three categories, accounting for 10 %, 35 %, and 50 % of the total annual coffee production, respectively. However, coffee plantations are owned by state farms or private investors. Coffee is the primary income source for more than five million smallholder growers and contributes to 95 % of the country's output [74,76,77]. Nearly 15 million people in this country rely on this sector as their primary source of income [74,78]. However, smallholder farmers find themselves at the bottom of the chain. They are also estimated to receive 60 % of the export prices which is much lower than major coffee producing countries like Brazil (90 %) [43]. They also face challenges such as limited farm plots, insufficient capital, lack of market price information, lack of modern technologies, poor institutional support, and low bargaining power [43,76,79–81].

The Ethiopian coffee value chain consists of production, collection, processing, marketing, exporting, and consumption stage. There are two major categories of actors involved in the coffee value chain: primary and secondary actors. While smallholder coffee farmers, farmer cooperatives, cooperative unions, processors, traders, exporters and buyers are the primary actors; government institutions, private institutions and service organizations are the secondary actors [73,80, 82–85]. Table 1 shows the details of the actors and their major roles in the Ethiopian coffee value chain.

On the marketing side, the Ethiopian Commodity Exchange (ECX) was established in 2008 with the aim of trading agricultural products, particularly coffee, and streamline the coffee marketing system [86]. The platform aimed to facilitate the connection between coffee producers and buyers by providing necessary information to reach an agreement on prices. ECX also maintains a high standard for coffee, adjusting its grades based on market demand, which attracts buyers. Nevertheless, until 2017, the strategy restricted direct coffee exports from individual farmers to buyers, permitting exports exclusively from commercial coffee farms [74,76,86,87]. This restrictive system has increased the marginalization of smallholder coffee growers, limited their access to market information, and reduced their bargaining power. The system failed to develop the specialty coffee industry because of a lack of traceability, which makes it difficult for smallholder coffee producers to get a premium price. These bottlenecks compelled the government to reform the coffee marketing system to a so-called 'vertical integration system' in 2017 [76]. In this strategy, smallholder farmers can sell their coffee through seven channels: directly to ECX, domestic roasters, international buyers, out-growing farms, suppliers, suppliers' brokers, and cooperatives. The assumption was that the platform would allow farmers to directly export their coffee to international markets. It would also create a conducive environment for suppliers to participate in the coffee production and also create close collaboration between the farmers and suppliers. The system has intended to ensure women's participation in the coffee value chain. Furthermore, the vertical system enables for traceability, which promotes the growth of specialty coffee production at premium pricing for high-quality beans.

3. Research methods

3.1. Study area

For this study, we conducted quantitative surveys, focus group discussions and semi-structured interviews in the coffee production zones of Jimma and Illubabor. The subsequent interviews were also conducted in Addis Ababa which is home to many coffee stakeholders. Gera,

Table 1
Actors category and their main functions.

Actors Category	Specific actors	Main functions
Input suppliers	Ministry of Agriculture, research and academic institutes, private input suppliers, agro-enterprises, NGOs, etc.	They supply improved coffee seedlings, farm tools, pesticides, fertilizers (organic and inorganic), extension support, technical assistance, financial and credit provision, insurance, etc.
Coffee producers	Smallholder coffee farmers (i.e., those farmers who have <0.5 ha of coffee land). They contribute 95 % of the nation's total coffee production.	They carry out the activities such as farm management, harvesting and postharvest handling, cherry harvesting and drying, transporting to hulling or washing stations, loading and unloading, sorting, grading, and selling red cherry to local collectors, primary cooperatives, processors, private investors, local consumers and retailers, etc.
Primary farmers cooperatives	All coffee cooperatives at kebeles	Members of cooperatives participate in collection of red and dry cherry coffees, sorting, fermentations, hulling, packing, fermenting, warehousing, polishing, and blending and transporting, etc.
Cooperative unions	Kata Muduka, Limu Inara, Sorgaba, Oromia, Sidama, Yirgacheffe, Kafa Forest, and Bench Maji Coffee Farmer Cooperative Unions	They engage in activities such as hulling, polishing, and blending for the parchment and polishing and blending for sun-dried coffee. They also supply farm inputs, arranging transport service, collecting, processing, facilitating savings and credit service, provision of warehouses, promotion and exhibition, ensuring supply of organic coffee and exporting, roasting, look for global markets to sell coffee and share dividends to the cooperative members, etc.
Collectors	Representatives for suppliers (middlemen) who can collect coffee from any sources, except cooperative memberships	They buy coffee from smallholder farmers at lower prices and sell it to primary coffee farmers' cooperatives, processors, and exporters. They also collect, transport, process, store and market, etc.
Processors	Millers (center for washing and drying stations) such as rivate investors, cooperative unions, local collectors	Process red cherry coffees into parchment and green beans through hulling, pulping, drying, washing, fermenting, sorting, grading; packing, weighing, storing, and selling to either foreign markets, exporters, or retailers, etc.
Wholesalers	They are mostly individual traders who have wholesale trade licence	Wholesalers involve in buying local standard coffee from suppliers and reselling to retailers. They purchase both washed and unwashed coffee with various standards.
Retailers	They are mostly individual traders who have retail trade licence	Retailers buy coffee from domestic wholesalers and sell it to local consumers.
Exporters	Private investors, individual farmers (have greater than 2 ha of coffee land), cooperative unions	They undertake the activities such as buy coffee from farmers, collectors, unions and other privates. They buy coffee from suppliers, reprocess and market to international buyers. They engage in cleaning, sorting, grading, cupping, storing and exporting. They also carry out the processing activities such as hulling and other value-adding chores such as colour sorting, polishing and blending.
Regulatory institutions	Ethiopian Coffee and Tea Authority, Ministry of Trade, Ethiopian Commodity Exchange	Develop policy and strategies, manage market governance system, manage coffee production activities to end consumption, maintains coffee's quality standards, facilitate coffee producer-buyer connections, manage auctions, provide necessary market information, adjust coffee grades based on market demand, build transparency, etc.
Supportive institutions	Government institutions, national and international organizations	They engage in policy formulation, advocacy, promotion, research, provision of information and technology, financial and credit service provision, facilitation of market linkages and creation of business environment, etc.

Gomma, and Limu Seka were selected from Jimma Zone, whereas Yayu and Ale were chosen from Illubabor Zone. There are also various institutions that play a major role in the coffee production and marketing in these selected areas, although their contributions vary. Following this, six kebeles (lower administration level) from each district were randomly selected to conduct the survey and focus group discussions. This strategic choice leverages purposive sampling, allowing researchers to apply their judgments in a manner that addresses research queries

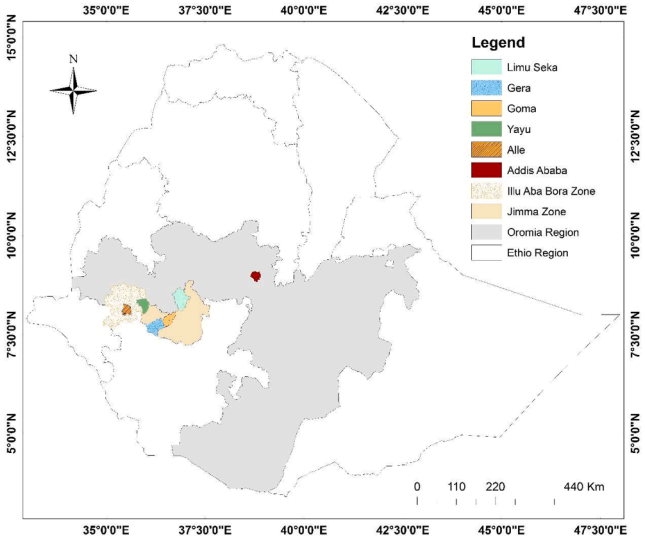

Fig. 1. Map of the study area.

[88]. Fig. 1 shows a map of the study area.

These districts have highland, midland and lowland areas with an average temperature and annual rainfall: Ale (18.775 °C, 3064.55 mm), Yayu (20.96 °C, 2089.1 mm), Gera (16.97 °C, 2812.1 mm), Gomma (16.97 °C, 2812.1 mm), and Limu Seka (19.995 °C, 2093.9 mm). All these selected areas are known in coffee production and other agricultural production activities. Most smallholder farmers in all districts are engaged in coffee production. In 2024, the total coffee production in each district was: Yayu (36,747.55 tons), Ale (493 tons), Gera (29,116.977 tons), Limu Seka (23,868.685), and Gomma (37,285.08 tons). Other cash crops, such as khat and commercial trees, are currently expanding in these areas due to climate changes.

3.2. Sampling procedures and data collection

A mix of quantitative and qualitative methods was used in this study. First, we conducted a survey to assess the impact of climate change on the coffee sector. Six kebeles from each district were chosen using stratified sampling techniques. The stratifications were based on the agroecological zones of highland, midland, and lowland, taking into account their altitudinal and topographic features. Accordingly, 203, 211, 202, 204, and 200 smallholder coffee producers were chosen from Yayu, Ale, Gera, Goma, and Limu seka, respectively. We considered kebeles with altitudes of lowland (<1500 m.a.s.l), midland (1501–1799 m.a.s.l), and highland (≥1800 m.a.s.l) [89]. Overall, 1020 smallholder coffee farmers were interviewed.

We used closed-ended questions to gather insights into farmers' perceptions of climate change, specifically its impact on coffee production, processing, storage, and transportation. The questionnaires were initially prepared in English and were later translated into the local language (Afan Oromo). We also conducted a pilot survey to test the design of the questionnaire before full deployment and allow enumerators to practice data collection. We stopped the pilot study once we ascertained overall interview time, the reliability of the survey tool used, and the appropriateness of the questions included in the survey. The data were collected using Kobo Toolbox, an open-access digital survey tool that can be deployed on smartphones and tablets. Answers can be stored on local devices and later uploaded to a cloud server [90]. Since most of the respondents live in remote areas where there is no internet access, this digital tool helped us properly collect data. We then exported the collected data in CSV and SPSS formats.

Additionally, we also gathered qualitative data to gather insights into the impacts of climate change on Ethiopian Arabica coffee production and its supply chain. Semi-structured interviews and focus group discussions were conducted to acquire the data. These data collection methods provide a good opportunity to collect in-depth data on people's views, beliefs, and experiences in the research area. We conducted semi-structured interviews with coffee stakeholders utilizing a bottom-up approach from district to federal levels, involving participants from public, private, and civic institutions using snowball sampling technique. Snowball sampling was employed to ascertain the total number of participants for the interviews [91]. This method enables an institution to recommend other institutions involved in climate interventions within the coffee sector. To reduce the biases associated with the snowball sampling method, we collected data from diversified sources and triangulated them. Use of varied data sources is a good mechanism to reduce biases associated with the snowball method of sampling [92]. 67 key informants were interviewed to address the research question. Before starting the interviews, we prepared an interview guide that consisted of a list of checklists used during the interviews. The checklists were translated into the local language prior to the interviews. Most upstream actors were interviewed in Afan Oromo, whereas downstream actors were interviewed in Amharic or English. We collected data using a recorder or a note-taking method. Additionally, consent forms were used to ensure the interviewees' willingness, informedness, and positive emotions before and after study completion. Each interview lasted 45–90 min. The interviews were conducted with high ethical standards, ensuring participants' anonymity, and choosing conducive locations to foster open dialogue. Table 2 provides information on the institutions, geographical locations, participants, interviwee position, number of interviewees, and institutional functions.

Finally, focus group discussions were conducted to obtain in-depth information about the research topic. While conducting the focus groups, the debate was held in a laid-back setting to allow the participants to express themselves freely. An experienced moderator led the discussion with the help of an observer who took notes and set up recordings. Each group consisted of 9–12 participants and was conducted at the same 30 kebeles in five districts where we collected survey data. Overall, this study involved group discussions with a total of 367 participants. Each discussion lasted between 54 and 104 mins.

3.3. Data analysis

The analysis includes both surveys and qualitative data. The survey data was analysed using SPSS software for data coding and descriptive analysis, while the results were graphically presented using R software. Regarding qualitative data, the transcripts of the interviews and focus group discussions were translated into English after converting audio recordings into text. The data were then thematized using NVivo 14 software, which included farmers' perceptions of changes in temperature and rainfall patterns, disease and insect pests, extreme weather occurrences, effects of coffee shifting, expansion of khat and other commercial tree cultivation. Institutional perspectives on how climate change affects coffee cultivation, processing, storage, and transportation along the coffee supply chain are also included in the analysis.

4. Results

Finding 1: There are changes in temperature and rainfall patterns in coffee production areas.

The study reveals that climate change is currently occurring. The indicators are rising temperature and rainfall pattern changes. One informant stated that

> Climate change has been noticeable in recent years. Some indicators of this phenomenon include irregular heavy rainfalls, prolonged rainy seasons, unpredicted rainfall patterns, early onset of the fall season, and increased temperatures. (GO11)

According to the survey results, 76.7 % of respondents reported an increase in temperature (Fig. 2). The deviation from the average temperature required for coffee can have an impact on coffee production. The impact of rising temperature has resulted in a shift in coffee cultivation from lowlands to highlands.

The group participants also state that changing rainfall patterns, especially heavy rainfall or delayed onset rainy seasons, significantly impacted coffee production. Untimely rain causes scattering of coffee flowers and fruits, leading to a decline in coffee production. One participant stated

> After the coffee blossoms, we see the flowers; we are happy, and we thank God. We then mourn the heartbreaking sorrow after the untimely rain falls too much and scatters its flowers. (FGD conducted at Wabu kebele, Yayu district)

The survey result indicates that there has been an increase in the average amount of rainfall, intensity, and longevity (Fig. 3). However, high rainfall and unpredictable seasons significantly impact coffee production during harvesting, while delayed onset seasons often affect coffee flowering or ripening.

Our interviewees further indicate that changes in temperature and rainfall patterns are drivers of extreme weather events, agroecological changes, and environmental stress. They exacerbate the decline of coffee output, resulting in price fluctuations, low income, and food insecurity

Table 2
Institutional types, interviewees (anonymized) and their major functions in the Ethiopian coffee value chain.

Institutional category	List of institutions	Geographical locations	Participants (Anonymized)	Interviewee position	No. of interviewees	Major functions
Farmer cooperative	Primary Coffee Farmers Cooperatives	Gomma, Ale, Limu Seka, Gera	CO1, CO5, CO6, CO7, CO8, CO11, CO12	Experts and Head in Cooperative, Experts in Marketing, Business Management	7	Farmers participate in training, implement climate adaptation practices, participating in forest and land management practices, improve coffee yield and quality, ensure sustainable coffee production, and share information with other farmers.
Cooperative Unions	Limu Enara, Sorgaba, Katta Muduka, Oromia Coffee Farmers Cooperative Unions	Limu Genet, Mettu, Addis Ababa, Gomma, Limu seka	CO2, CO3, CO4, CO9, CO10	Managers, General Manager, Board Chairperson and investor	5	Unions provide technical training, coffee production inputs, modern equipment for coffee processing, improve coffee yield and quality, and promote climate resilience strategies.
Membership organization	Ethiopian Coffee Exporter Association	Addis Ababa	MO1, MO2	Head of Marketing and market research, General Manager	2	Promote global coffee, advocates for policies and regulations, provides member information, supports capacity building, and collaborates with international organizations like ICO to expand market opportunities, etc.
Market and development	Trade and Market Development	Gomma, Yayu, Limu Seka	AG1, AG15, AG18	Experts in market management	3	Develop policy and strategy, collaborates with Ethiopian Coffee and Tea Authorities, ministry of Trade, and other organizations, market regulation, providing training, maintaining coffee quality standard, facilitating farmer linkages and export networks, etc.
Government organizations	Ministry Of Agriculture (Bureau of Agriculture)	Ale, Gomma, Limu seka, Yayu, Gomma	GO1, GO2, GO3, GO4, GO6, GO8, GO9, GO10, GO11, GO12, GO13, GO14, GO15	Experts, team leaders, Head/Vice Head of Agricultural Office	13	Develop policy and strategy, provide capacity-building training, provide extension services, adjusting accessing coffee production inputs, promoting sustainable coffee production practices, sustainable land management, liaising farmers with various institutions, linking farmers with markets, supervision and monitoring, etc.
Agency	Ethiopian Commodity Exchange	Mettu	AG10	Expert in coffee control and management expert	1	Establishes platforms for coffee sellers and buyers. Ensures the quality of coffee by enhancing climate-resilient infrastructure, etc.
	Ethiopian Coffee and Tea Authroity	Gera, Limu seka, Alle, Addis Abeba	AG2, AG3, AG4, AG13, AG16	Experts in coffee production and quality, Experts in market management, Director Manager	5	Formulate policies, regulating market activities, promoting coffee industry growth, supervising production processes, research and development, and providing international grades and certificates, etc.
	Environmental Protection Authority	Ale, Gera, Limu seka, Yayu, Gomma	AG5, AG6, AG7, AG8, AG9, AG11, AG12, AG14, AG17	Experts, Head Office	9	Provide capacity-building training, promotes sustainable environmental protection activities, triggers participatory forest management, sustainable land management, water and pollution control, and biodiversity conservation, coordinate policy and strategies for climate resilience implementations, promotes eco-friendly coffee processing, and so on.
	Busa Gonofa	Jimma Zone	GO5	Expert, Head Office	1	Resource collected by the community to aid each other during natural and man-made disasters. This cultural of mutual assistance, rooted in the Gada system, plays a crucial role

(*continued on next page*)

Table 2 (*continued*)

Institutional category	List of institutions	Geographical locations	Participants (Anonymized)	Interviewee position	No. of interviewees	Major functions
						particularly in country (Oromia)'s development.
Research Institute	Jimma Agricultural Research Institute	Mettu	GO7	Focal person	1	Provides capacity building training for extension workers and farmers, conducts actionable research, releases new coffee varieties (drought and disease-resistant coffee types), provides on-technical assistance at farm, promotes sustainable coffee production practices, provides coffee production inputs, promotes agroforestry based coffee production, etc.
Private Business	BNT Industry and Trading PLc, Fairchain Coffee Agro Processing Plc, Abana coffee PLc, Tracon Agricultural and Trading PLc, MIDROC Coffee Plantation (2), Ayetu Agricultural and Trading PLc	Addis Abeba, Limmu Genet, Gera, Gomma	BUS1, BUS2, BUS3, BUS4, BUS5, BUS6, BUS7	Managers, Experts	7	Private investors provide training, financial support, coffee and shade tree seedlings provision, infrastructure development, environmental conservation awareness, technical support, improved coffee variety, agroforestry practices, climate resilience strategy promotions, carbon footprint reduction, and modern technology dissemination for coffee processing, etc.
Development Organizations (NGOs)	Reducing Emissions from Deforestation and Forest Degradation	Ale, Yayu, Gera, Gomma	SO7, SO8, SO9, SO14	Focal persons, Project coordinator,	4	Provide training on agroforestry restorations, sustainable forest management, sustainable land management, and deforestation reduction strategies to enhance capacity-building skills: promote solar energy adoption, sustainable farming practices, and agricultural diversification strategies to reduce climatic risks; provide the necessary information and resources to make the implementation more effective, etc.
	German Agency for International Cooperation	Ale	SO1	Program component manager	1	Provides financial assistance, technical expertise, and training for farmers and extension workers; promote climate adaptation strategies, provides coffee processing equipment, and encourages the use of improved coffee varieties; disseminate modern technologies to farmers, promotes sustainable forest management, and encourages integrated pest management to ensure effective agricultural practices.
	EU-Coffee Action for Ethiopia	Yayu	SO6	Focal person	1	Supports coffee production by training farmers, collaborating with organizations, conducting research, liaising public-privates, providing certifications, extension services, and inputs, etc.
	TechnoServe	Gera	SO13	Business and agronomy consultants	1	Engages in coffee production by providing training on climate resilience strategies such as agroforestry practices, soil and water conservation, and sustainable forest management, etc.
	Hunde Oromo Grassroot Development Initiatives	Gomma	SO10	Focal person	1	Provides training on sustainable agricultural practices, financial assistance and credit services, coffee processing equipment (materials and machines),

(*continued on next page*)

Table 2 (*continued*)

Institutional category	List of institutions	Geographical locations	Participants (Anonymized)	Interviewee position	No. of interviewees	Major functions
						technical support on climate adaptation and mitigation practices, coffee and tree seedlings, and the establishment of demonstration and nursery sites, etc.
	Nature and Biodiversity Union	Yayu	SO3	Focal person	1	Conserves nature, habitat, biodiversity, and support livelihoods, etc.
	Environment Coffee Forest Forum	Yayu, Addis Ababa	SO2, SO4	Coordinator of the project, Executive Director	2	Provides training on sustainable coffee production practices, conducts research, participates in coffee agroforestry systems, promotes sustainable forest and land management, works on climate adaptation and mitigation strategies, serves as a liaison between science, policy, and practices, develops carbon credit projects, establishes demonstration and training centers, and supplies improved coffee varieties, etc.
	Digital Green Foundation	Gera	SO11	Focal person	1	Provides improved coffee varieties, video-extension training, promotes forest management, climate-copying techniques, financial assistance, shade tree seedlings, and sustainable land and forest management, etc.
	Hanns R. Neumann Stiftung	Yayu	SO12	Project coordinator	1	Provides capacity-building training, provides coffee production equipment, promotes forest management, provides improved shade and coffee seedlings, promotes agroforestry practices, and promotes climate-coping mechanisms to enhance sustainable coffee production, etc.

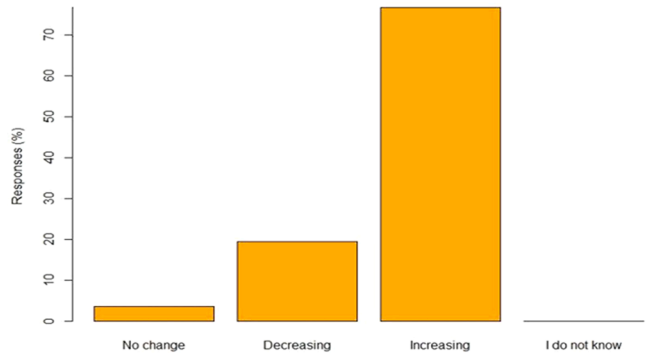

Fig. 2. Perceptions of coffee farmers towards changes in the average temperature over the past decade.

(AG5,7 8,14, GO7, SO5,7,10). Some interviewees further perceived that climate change impacts the coffee industry's supply chain, distorts market channels, decreases export volumes, and causes customer losses (AG11 and SO2). One key informant explained that

> Climate change indeed exists. The indicators are change in rainfall, temperature, humidity, flood and landslides. This caused land degradation, soil erosion, change agro-ecological zone, reduction in coffee production and productivity, price fluctuation, food insecurity, migration, life instability, etc. (AG5)

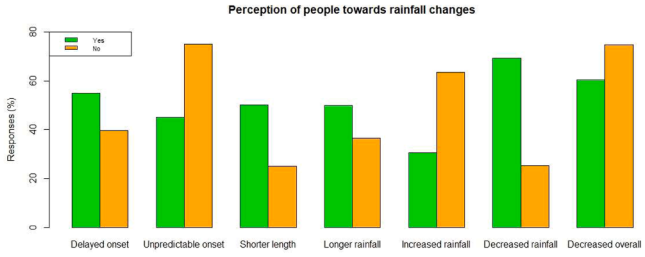

Fig. 3. Perceptions of coffee farmers about changes in timing of rainfall patterns over the past decade.

Furthermore, a recently undertaken trend analysis also shown that mean annual and seasonal rainfall has increased significantly in the Gomma, Gera, Limu Seka, Yayu, and Ale districts in southwest Ethiopia [93]. The result also revealed that the minimum and maximum temperatures have also been steadily increasing in these areas. Rising temperatures pose a significant threat to lowland and midland coffee-producing regions, while highland locations may become future coffee production hubs. Altering rainfall patterns could also potentially negatively affect coffee production in highland regions. The finding generally showed that rising temperatures and changes in rainfall patterns would have a negative impact on coffee phenological stages, lowering yields and quality. The study thus underscores the urgent need for effective implementation of sustainable coffee production practices

to enhance the coffee sector's resilience.

Finding 2: Coffee diseases are currently posing significant challenges to coffee production.

The interviewees identified coffee berry disease (CBD) and coffee wilt disease (CWD) as the most common diseases currently affecting coffee production (AG3, AG16, BUS2, CO12, GO9, 12, 13, AG5, MO2). According to their report, these diseases affect coffee production not only in some specific villages but are also widespread everywhere. The farmers describe the effects of the diseases as causing "the blossoms to wilt and the roots and stems to rot" (FGD2). Another group describes

> There is a disease called 'corona' that causes the coffee to dry quickly and scatter. The disease starts to attack as soon as coffee starts to bloom or flower. The difficulty with these epidemics is that they make farmers vulnerable to famine and worry about their future. (FGD conducted at Genida Chala kebele, Gera district)

Farmers also highlighted that their village is famous for coffee production; however, due to disease, production has recently been declining significantly (FGD16).

> The disease affects coffee by heating the stems and burning leaves, starting to shed the flowers, and eventually dropping down the coffee. The disease torture destroys coffee trees and scatters coffee beans. (FGD conducted at kolakimbibit kebele, Gera district)

Farmers have tried various methods to combat diseases, but these are not very effective. Their reports indicated that these methods are conventional. For example, the farmers described the methods as follows:

> We burned and removed disease-infected coffee trees that have proven unsuccessful in achieving our goals. (FGD conducted at katta Bero kebele, Gomma district)

Finding 3: Extreme weather occurrences have significantly impacted coffee production and the livelihoods of farmers.

The survey results indicate that, over the past decade, coffee farmers have experienced weather events compared to previous years. The frequencies of floods, heavy rain, storms, droughts, and landslides were relatively low (Fig. 4). However, landslides are currently expanding in 10 districts, including Gera, Gomma, Shabe Senbo, Sigmo, Setema, Gumay, Nedi Gibe, Seka Chekorsa, Sokoru, and Dedo (Fig. 5), but only in the Jimma areas (GO5).

The discussants also asserted that landslides seriously devastated a coffee farm in Limu Seka district, causing major coffee output losses (FGD20, 23). It displaced >300 people in the town of Gera. The interview reports further indicated that landslides caused significant damage to coffee production in the Yayu (SO7) and Gomma (CO6) districts. Consequently, many districts are prone to natural calamities, particularly during the summer, when excessive rainfall is prevalent. One of the group participants was concerned that:

> My most frightening fear is that I do not think this natural disaster, especially landslides, will stop in affected districts. I have serious concerns that landslides will continually affect these districts and expand to other districts in the future. (GO5)

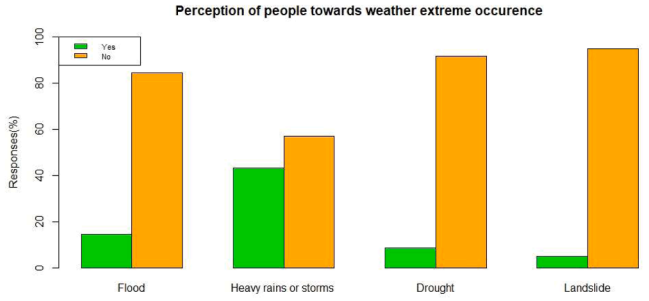

Fig. 4. Experiences of coffee farmers facing significant reductions in household income, assets, or consumption due to extreme weather events.

Heavy rains, ice, floods, landslides, droughts, and frosts are the most common extreme weather events in Ethiopian coffee-producing areas (AG11, CO6, 10, SO7). Heavy rain, ice, floods, and landslides are more prevalent in the summer, whereas droughts are severe in the spring and summer, and frosts are more prevalent in autumn and winter (AG8, GO13, SO2, 7, 14). These disasters have put coffee production at risk (AG5, 7, 8, CO11, GO13, SO2, and 14). Many districts are also prone to natural calamities, especially during the summer season when excessive rainfall is prevalent. One group of participants states that

> Although we harvest coffee every year, if there are such adverse effects, we can expect coffee to begin producing after three years. The output was therefore insufficient, even for home consumption. We have tried many things that we thought would solve this problem, but we have not found a solution yet and it is beyond our power. (FGD conducted at keto gelecho kebele, Ale district)

Heavy rain mixed with ice significantly affected coffee production. Ice damages coffee leaves and flowers (AG3). It also damages coffee stems, scatters the leaves, and eventually leaves the coffee barren, which decreases coffee production (CO9, FGD3,5,10,14,28, GO13). The discussant states,

> In previous years, we have been obtaining large yields, but this year, production has decreased significantly due to heavy rain and three rounds of heavy ice, leading to the destruction of coffee and lower profits for farmers. This year, we never experienced a sudden breakdown. (FGD conducted at Getabore kebele, Gomma district)

Ice damaged coffee stems and dispersed leaves, resulting in lower yields than in previous years (FGD14). In addition, discussants reported that coffee plantations became unsustainable in the absence of shade trees, such as the popular Albizia, which was severely damaged by ice and excessive rainfall last year (FGD13).

Frost also poses a significant threat to coffee production by damaging the coffee trees, leaves, flowers, and stems. This problem is more common in the highland areas. Frosts burn and destroy coffee trees (FGD13). One participant stressed

> Rain mixed with frost causes the coffee to dry after blooming and fruiting. There is no other way to recuperate from such a natural disaster, but to pray to an almighty God. (FGD conducted at Kadamansa kebele, Gomma district)

Frosts decrease coffee yield, which subsequently affects the livelihoods of farmers (AG17, FGD1,13,17,19, GO13,14). One participant said

> The yield obtained from the cultivation of coffee decreased because of frost. If such problems persist in the future, coffee production may be stopped, and farmers will switch to other agricultural production. (FGD conducted at Koma kebele, Limu Seka district)

This study reveals that severe drought has been a significant challenge for coffee output over the past four years. For example, due to prolonged drought last year, coffee production has dramatically decreased, exposing farmers to several problems (FGD1). One farmer said

> Our farmers obtained several yields per hectare, but this has been decreasing this year. Trees that serve as shelters for coffee also dry. (FGD conducted at Tesosadacha kebele, Gomma district)

A prolonged dry season causes significant damage to coffee cultivation (FGD21). Participants noted that prolonged dry periods led to water stress, plant withering, flower abortion, and decreased coffee production. One interviewee explained:

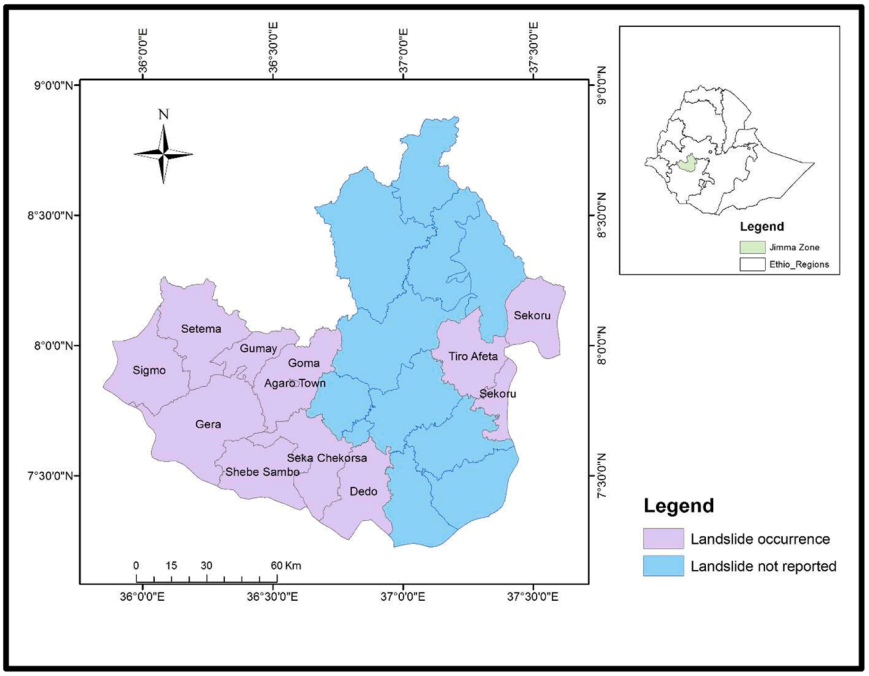

Fig. 5. A map showing the districts where landslides occurred in southwest Ethiopia.

Although the Gera district has never experienced drought due to effective forest conservation methods, increasing temperatures during coffee harvesting seasons have lowered production rates. (AG2)

The participants also mentioned specific concerns such as the decline of coffee shade trees, particularly in lowland areas, which are crucial for coffee cultivation (FGD13).

Finding 4. Climate change has led to shifting of agro-ecologically suitable coffee areas, with significant effect on social, economic, and environmental aspects.

Coffee plantation is currently shifting to highland areas (AG1,4, 6, BUS1, 2, CO4, 6, GO2, 10). Owing to the rise in temperature, coffee is currently grown in areas where it has not been grown previously. Areas that were good for coffee became less suitable as temperature increased (SO1). One participant highlighted this change:

Due to climate change, the area coverage for coffee production expanded from 16 to 24 Kebeles in the Gera district. Concurrently, forested areas have been repurposed for crop and coffee production. (AG6)

Participant (AG6) observed a significant temperature increase from 17 °C to 25 °C in the highland areas of the Gera district, indicative of a shift towards mid-altitude climate conditions. This warming has facilitated the migration of coffee cultivation from lower to higher elevations as lower zones experience desertification (AG6). Other participants also noted the widespread occurrence of droughts that affect coffee yields.

In our district, 38 kebeles are the dominant coffee-producing areas, except for six kebeles, which are now desert areas and unsuitable for coffee production. (GO7)

One informant explained that desertification was widespread in Gomma District a few years ago (AG1). Discussants assert that people living in desert areas are missing coffee crops. People living in highland areas can obtain better coffee yields if they take care of the coffee properly (FGD12, 13, 14). One participant added

There is a chance of diversifying coffee in highland areas because currently, highland areas may be shifted to mid-and lowland areas. (BUS1)

Climate change results in increasing temperatures and moving coffee from lowlands to highlands. However,

People living in the highland areas are highly populated. The number of people per meter of area in the highlands was greater than that in the lowlands. However, the country's land tenure system is restricted, and it cannot move from one place to another. They do not allow us to move coffee from the lowlands to the highlands. This also affects the coffee production methods. This is the main problem we currently face. (AG4)

The interviews further illustrated the comparison of coffee production in highland and lowland areas, their implications, and the global market demand for these coffees. One informant explains,

Lowland coffee production produces more yield but is of lower quality than highland coffee. The international market we compete with is not only interested in the volume we produce but also in the quality of the coffee we supply. Thus, with poor-quality coffee, we do not have the power to bargain in the international bid in New York. (AG4)

The expansion of coffee cultivation into highland areas has led to deforestation and biodiversity loss driven by increased land demand for coffee production (SO2, FGD15). Low production was observed in lowland areas where labor intensity was very high (GO2).

The adaptability of different coffee varieties varies significantly across agro-ecological zones. One participant noted

Some coffee varieties suitable for lowland areas are not effective in midland or highland areas, showing extensive variability caused by climate change across different zones. (AG6)

This variability extends to soil fertility, with increasing soil acidity further complicating coffee cultivation (BUS2). The shift in coffee production from lowland to highland areas can disrupt coffee market channels, resulting in price volatility, market instability, and client loss (AG4, GO4, 12, CO9, and GO).

Finding 5: The expansion of Khat and other commercial tree plantations is currently affecting coffee production.

We found that despite coffee production being the dominant sector,

khat cultivation is rapidly expanding in every village. According to the informants, climate change is currently pushing coffee producers to cultivate khat and eucalyptus trees as alternative sources of income (GO1, 2, CO5, SO2, and SO4). When comparing benefits,

> Because of the high price, our farmers prefer khat to coffee. They can harvest khat three or four times a year. They obtain better prices from khat. After planting coffee, farmers must wait for at least three or more years to harvest it. However, we influence them to produce by using a premium price. (CO4)

The discussants reported that the current expansions of Eucalyptus, Juniperus procera, Grevillea, and Khat cultivation are interfering coffee production (FGD17). Farmers highlighted that coffee production does not have a distinct zone but rather coexists with other agricultural activities. One informant says,

> However, the previous coffee farm was completely replaced with a khat [farm] in Harar. Khat is currently expanding to Southwest Ethiopia and other areas. The environment is highly changed, and it is difficult to adapt to the environment in the previous coffee growing areas. The production and quality of coffee are significantly altered. Currently, the soil is highly degraded and acidic. However, in the Limu area, most coffee land has been converted into cereal crops. Currently, irrigation is used for wheat and cereal crops. (BUS2)

When there is no chance to produce any other agricultural product to substitute coffee for three years, farmers whose livelihoods are fully dependent on coffee production face major difficulties (FGD1). participant said

> Currently, the income I receive from coffee is insufficient. This only serves the domestic consumption. Now, it is forcing me to stop production and move on to other products. (FGD conducted at Kundi kebele, Ale district)

The interviews further revealed that farmers are replacing coffee with khat due to its higher income, resilience to climate change and disease, easy management, and less labour-intensive nature. While coffee takes three–four years to harvest, khat can be harvested three–four times per year. However, the major concern for the future is that as khat production increases, the possibility of coffee production is threatened (CO5, GO1, CO4).

Finding 6: Climate change has a considerable effect on coffee processing, storage and export.

We found that climate has a negative impact on the coffee industry, influencing its production, processing, storage, and transportation (GO2 and MO1). Climate has decreased coffee yield, degraded coffee quality, reduced humidity content, and eventually lowered coffee grades (AG10). This issue stems primarily from the lack of modern machines for washing and drying coffee.

One participant explained that climate change directly affects the humidity content of coffee beans, with fluctuations either below or above the average (BUS3). Coffee quality is significantly influenced by its average moisture content, which normally ranges from 11.5 to 12 %. However, maintaining humidity at the destination remains a challenge in Ethiopia. This issue is primarily exhibited when coffee is transported in extremely hot or cold environments (BUS3). The informant explains

> Most coffee suppliers face problems with moisture control and ventilation, which makes it difficult for them to provide clients with high-quality coffee, ultimately leading to customer loss. (BUS3)

The presence of high humidity in roasted coffee significantly reduces its aroma and flavour and promotes mould growth. When roasted beans are exposed to high temperatures, they lose their quality and develop an unpleasant flavour. This issue mostly occurred when coffee companies failed to deliver coffee to buyers on time (BUS2). One informant explains

> However, farmers are challenged to adjust their temperature owing to the lack of modern equipment. (CO3)

Regarding coffee storage, the interviewee explained that the longer the coffee stays in the warehouse and the higher the temperature, the drier the coffee (MO1). Excessive cold causes coffee to rapidly absorb moisture, resulting in an increase in its moisture content from 12 %. This promotes the development of mould, because coffee instantly changes with climate change (MO1). This results in weight loss and deterioration of quality. In fact,

> We do not have a temperature-regulated warehouse. Although we lack the sophisticated processing and storage facilities that Brazil does, we do what we can. (MO1)

This shows that climate change has negatively affected the coffee sector, from production to consumption (AG7 and AG3). Likewise, coffee quality affects the supply and demand of both domestic and foreign markets. This problem has also had a negative impact on the income of coffee exporters and the country's GDP (AG8). One informant mentioned

> The primary effects of climate change on the coffee industry include a decrease in production, decline in coffee quality, market volume disruption, price volatility, and loss of customers. (GO7, AG11)

Therefore, this study underscores the significance of adopting modern coffee processing, storage, and export equipment that can adjust to changing temperatures, thereby enhancing the resilience of the coffee quality.

The results indicate that climate change has disturbed coffee market channels, causing loss of clients, price increases, and coffee market volatility (GO4). Moreover, the pervasive effects not only threaten the economic viability of coffee production, but also disrupt the natural environment, compel migration, and perpetuate cycles of poverty and food insecurity among farmers (AG8). This environmental instability underscores the vulnerability of coffee production to climate variability, reflecting the broader concerns in ecological economics regarding the sustainability of agricultural practices in the face of climate change. These findings underscore the urgent need for comprehensive adaptation strategies to mitigate the impact of climate change on this vital industry.

Table 3 presents the summary results for the impact of climate change on the coffee value change. The table also depicts the impact of climate change on sustainable development on socio-cultural, economic, and environmental dimensions in detail.

5. Discussion

Climate change can affect all actors in the coffee value chain, but in different ways and in different degrees [67]. Climate change is currently a major threat to Ethiopian Arabica coffee production and affects the coffee value chain. Temperature and rainfall pattern changes are the primary indicators of climate change, whereas extreme weather events, agroecological shifts, disease outbreaks, khat expansion, and post-harvest losses are the main consequences. Therefore, the discussion focuses primarily on a comprehensive understanding of how climate change impacts the coffee sector, along with its policy and practical implications.

Coffee producers rely on specific, predictable weather patterns such as rainfall, precipitation, temperature and humidity for their production [94,95]. In contrast, longer dry periods or heavy rainfall can lead to a decrease in coffee production. Minor variations in temperature and precipitation can also have an impact on a plant's ability to thrive [37]. The findings show that temperature increases have a negative impact on coffee output. Rising temperatures disrupt coffee flowering cycles and harvesting times, and can exacerbate over-drying, moisture loss, weight loss, and poor coffee quality. It can also accelerate drought, which

Table 3
Summary results for the impact of climate change on coffee value chain.

Climate change impacts	Main indicators	Coffee cultivation	Processing	Storage	Export	Sustainably impacts (social, economic and environment, etc.)
Increasing temperature	Rising temperature, Temperature fluctuation	Uneven ripening, fruit abortion after flowering, wilting of coffee trees, affect quality of coffee, create favour the development of diseases	Fermentation spoilage, over drying of coffee beans during drying, decrease weight of coffee beans, higher bean defects	Increasing evaporation and over drying of coffee beans, accelerates oxidization, increases chemical reactions, bad aroma and flavor, promotes fungal and pest growth, speed up mold and bacteria growth	Degrades quality, decrease export volume as yield is affected, customer /client losses, decrease reputation, increase bean defects	Agro-ecological changes, food insecurity, environmental stress, affect coffee farmers 'livelihoods, market instability
Rainfall pattern changes	Change in onset and offset rainy seasons, unpredictable rainfall, heavy rainfall, extended rainy seasons, earlier seasonal rainfalls, heavy rain mixed with ice, fluctuation of coffee flowering time	Disturbs coffee phenological stages, disturb flowering time, uneven flowering patterns and fruits setting, delays/enhance fruit maturity and ripening, drops of leaves, flowers and fruits during heavy rain, favour the development of diseases	Change in colour and odour, enhance bacterial and fungal growth, promotes beans rotting, accelerate mycotoxin contamination, promotes mold growth, disturb coffee drying time, shrinking/ swelling of beans, increase cost of processing (high rainfall during drying)	Decaying and rotting of coffee beans, change in colour and odour, bacterial and fungal growth increased, mycotoxin prevalence increase, promotes mold growth, shrinking/ swelling of beans depending on moisture content of the storage room	Increase beans defects, reduction in yield and quality, degrades coffee qulaity, reduce volume of market supply, customer loss	Market instability, food insecurity, economic stress (low income), environmental stress, soil degradation, agro-ecological changes, choose for other crops, affect the livelihood of the coffee farmers
Disease outbreaks	High prevalence of coffee berry disease (CBD) and Coffee wilt disease (CWB)	Wilting of coffee trees by CWD, reduce coffee plant photosynthesis process, affect the root system of coffee trees, drop coffee flowers, fruits and leaves, reduce coffee tree yields and quality, reduce shelf life of the trees, increase cost of production	Uneven roasting of coffee beans affecting final flavour, increase the percentage of mummified berries	Damage of coffee beans by insect such as coffee berry borer, weaken the beans and increase its susceptibility to insect damage, disease beans are prone to deterioration during storage leading to quality reduction	Increase beans defects, reduction in yield and quality, degrades coffee qulaity, reduce volume of market supply, customer loss	Reduce coffee yield, degrades coffee qulaity, economic instability, induces food insecurity, initiates other crop production
Climate extreme occurrences	Heavy ice, drought, floods, landslides, frequent frost, desertification	Coffee tree damage, drops coffee leaves, fruits and blooms; favour development of disease and pests, enhance flower abortion, destruction of shade trees and coffee trees	Promote bacterial and fungal growth, improper coffee drying, affect fermentation process	Promote bacterial and fungal growth, bad aroma and flavor, abnormal chemical reactions; mycotoxin contamination; decrease beans' weight and size	Degrade quality, market instability, decrease export volume, customer losses	Lower income, food insecurity, displacement, land use change, agro-ecology changes, environmental stress, increase social tensions
Agro-ecological zones shifting	Temperature changes, area suitability shift for coffee production, production expands to highlands, reduced coffee production in lowlands	Reduce the production of coffee in lowland areas, increase production of coffee in mid/ highland areas	Less functioning of fermentation and drying technologies in lowland areas. Lack of modern washing machines in mid/highland areas which increase cost of fermentation and drying technologies	Most storage rooms become nonfunctional in lowland areas, shortage of storage in highland areas leading to higher cost of production; enhance mold development in storage located at higher altitude	Less volume of coffee in lowland areas; increase volume of production in highland areas	Lower coffee production at lowlands, migration of coffee producer, affect coffee farmers' livelihoods in lowland areas; increase competition with other crops as highland is densely populated areas, social conflict, environmental stress, shortage of land in mid/ highland areas
Shifting to other crops	Expansion of khat (*Catha edulis)* production, encroachment of eucalyptus tree, Juniperus procera, grevillea, etc.	Substitution of coffee land by khat and commercial trees, reduce volume of coffee production	Reduces volume of coffee supply for processing machines, decrease millers, reduce income of coffee processing plants	Most coffee storage become nonfunctional, decreases millers	Decrease volume of coffee export, customer loss, causes internationally weak competition	Reduce volume of coffee production, reduce foreign currency, reduce country's GDP

causes irregular ripening of coffee cherries, fruit abortion, and physiological damage to coffee trees. Previous studies also showed that increased temperature can influence coffee physiology and coffee beans [35]. According to Wagner et al. [94], increased temperature had significantly affected flowering and harvesting times, thereby reducing coffee yield. A Mexican study also showed that temperature changes significantly reduced coffee yield [49]. Contrarily, despite existing temperature changes, Brazilian coffee farmers embraced technological integration to mitigate its adverse effects [96]. We also found that excessive and untimely rainfall significantly affected coffee production. Untimely rain can disrupt the growth, flowering, and harvest of coffee trees. Heavy rain can cause damage to coffee trees, which contributes to

the loss of flowers and fruits, as well as potential coffee tree collisions. It also accelerates moisture increases, promoting the spread of coffee diseases, pests, and fungal growth, leading to rotting of coffee beans and deterioration of their quality. Empirical evidences showed that heavy rains exacerbated soil erosion, leading to depletion of essential nutrients for coffee trees [97–99]. Heavy rainfall can hasten the likelihood of landslides and floods, which can severely affect coffee production. Generally, temperature and rainfall fluctuations affect farmers by reducing coffee output, decreasing income, and increasing vulnerability to climate change. This proves that climate change could have significant impact on Arabica coffee, especially in East African coffee-producing regions, as predicted by [45]. This necessitates sustainable agricultural practices, such as drought-tolerant varieties, tree planting, agroforestry, early warning systems, modern irrigation systems, and soil and water management, to ensure the sustainability of coffee production. Moreover, Chaichana et al. [37] found sustainable production practices, such as circular economy, green economy, emission of CO_2 reduction, and using digital agriculture, to enhance climate resilience in the coffee sector.

This study also highlights prevalent coffee diseases, including coffee berry disease (CBD), coffee wilt disease (CWD), and emerging diseases currently affecting coffee production. Climate change causes temperature and rainfall changes, which in turn exacerbate coffee disease outbreaks. Similarly, a prior study found that changing rainfall patterns and increasing temperature had contributed to an increase in disease incidences [37,52]. The spread of diseases varies across different agro-ecological regions. This is due to rising temperatures, which can accelerate disease spread from the lowlands to the highlands, improving their survival chances by increasing the number of host plants for their adaptations [100]. Moreover, heavy rains can increase humidity or precipitation, which can induce the spread of diseases [15,51,101]. This problem is particularly prevalent during the ripening, harvesting, and drying stages of coffee production. These findings further indicate the current prevalence of diseases causing coffee tree drying, leaf burning, and fruit scattering. These epidemics have significantly affected coffee yields and income, culminating in farmers falling into poverty. Farmers have attempted to eradicate diseases using both scientific and conventional methods, but their efforts have been ineffective, and their effects are worsening. Hence, Jamaican coffee growers had used integrated adaptive management methods to mitigate the impacts of diseases [102], this study also underscores the significance of enhancing coffee disease prevention strategies through integrated pest management, soil health management, and the adoption of resistant coffee varieties. Farmers have called for further research to identify the emerging diseases.

Ethiopian coffee producers are also currently changing from coffee production to alternative crops and commercial trees, which enables them to adapt to climate change and provide them with a better income. However, such a transition has social, economic, and political implications for the country as a whole, and coffee producers in particular. For example, the cultivation of khat and commercial trees increases farmers' incomes and improves their livelihoods [103–106]. This is due to the strain of climate change, which forces coffee producers to prioritize Khat and commercial trees over coffee production, putting future coffee production at risk. Nevertheless, it is difficult conclude that khat production always brings economic benefits unless supported by technological innovation, market access and policy support. For example, khat cultivation increases individual income and governmental revenue, which adds significantly to the country's economic growth; nevertheless, Ethiopia currently has no policy that supports or prohibits khat production [107,108]. Contrarily, khat has been either controlled or banned in many countries across the globe like China, UK and Netherlands [103,109–111]. Khat cultivation and usage are legal in Djibouti, Somalia, South Africa, and Yemen, but banned in Eritrea and Tanzania for possession and consumption. This suggest that legal disparities across countries are limiting khat's global export potentials, posing a greater future concern. However, while coffee has global market acceptance, khat is subject to a number of laws that limits its export. The failure to implement immediate climate adaptation techniques could thus potentially disrupt the global coffee marketing in the future. This predicament is currently prompting farmers to focus more on khat production that can withstand climate change. The increased expansion of khat cultivation will significantly impact the sustainability of coffee production, posing a paradox in both production and marketing aspects. However, the findings imply that because Arabic coffee has social, economic, and political implications for the country, it is necessary to pay greater attention to ensure its sustainable production. Therefore, this study urges policymakers to incorporate khat production into policy frameworks while also providing khat cultivators with the necessary support to strengthen their capacity to withstand with climate change and increase their income. Nevertheless, respecting farmers' interests and balancing coffee production and khat growth necessitate the innovative strategies.

According to the findings, the impact of catastrophes varies depending on their nature, time, and location. For example, landslides have not been widespread in Ethiopia in previous years but are now increasingly prevalent in coffee-producing districts, particularly those with highland areas, despite their uneven distribution. These disasters are most prevalent during the summer season when heavy rains fall. These incidents primarily occur in highland areas, where coffee production is abundant. Farmers in affected areas experience significant reductions in coffee production, resulting in low incomes and increased vulnerability to food insecurity. Moreover, landslides have caused displacement, migration, resource loss, and family separation, forcing people to depend on community, government, and international assistance. If landslides persist, the impact will reduce coffee market volume, lower quality, and potentially cause client loss. This calls for policymakers and practitioners to develop disaster risk preparedness, early warning systems, land zoning policies, and sustainable farming systems to ensure enhanced resilience in landslide-prone areas. Moreover, Ethiopia's coffee industry currently focuses on specialty coffee production in the highlands, but frosts wreak havoc in these areas. Frosts have a tremendous impact on the ecosystem of coffee farms, influencing soil nutrients, burning shade trees and grasses, lowering the canopy, and changing temperature and humidity regulations, posing a serious threat to coffee farms. To mitigate moisture losses, agroforestry systems, frost-resistant coffee varieties, mulching, and cover cropping are recommended adaptation practices. The previous studies also found that the impacts of extreme weather events had significantly reduced agricultural yields, resulting in food insecurity and lower farmer income [112,113], thereby perpetuating the poverty cycle. The effects will also have the potential to heighten social strains, economic crises, and environmental stresses, and hinder the country's economic growth. This study thus advocates early preventive and recovery strategies to mitigate natural disasters and climate-related threats to coffee production, emphasizing the need for interdisciplinary collaboration for sustainable agricultural practices. Moreover, the impact necessitates the urgent interventions like crop insurance since implementing crop insurance as a risk management strategy can enhance farm resilience to extreme weather events in agricultural production [114–117]. Thus, this research further advocates the use of sustainable farming practices, such as agroforestry systems, frost-resistant coffee varieties, mulching, and cover cropping, to reduce moisture loss from coffee farms.

We also found that climate change significantly affects coffee production by altering the land suitable for coffee production. This shift is due to changes in temperature, precipitation, rainfall, and altitude changes [62,93,94,118,119]. However, these effects have caused coffee production to decline in the lowlands and increase in the highland areas. Climate change is also driving private investors to shift to more suitable areas for coffee production. Dwellers are likely to either migrate to more coffee-suited areas or shift from coffee production to other crops to improve their livelihoods. The soil is also highly degraded in lowland

areas, which affects the coffee quality. It is difficult to consume lowland coffee alone unless it is blended with other types of coffee. However, areas previously unsuitable for coffee production in highland areas are becoming more suitable because of rising temperatures. Highlands are areas where specialty coffees are predominantly cultivated, which corresponds to the global market demand. This is because highland coffees have distinct qualities, flavors, and aromas that increase the market demand and premium pricing value. International buyers also demand single-origin, easily traceable, specialty, and premium coffee. Thus, coffee farming in highland areas provides investors with the possibility of expanding investments, market expansion, and access to networks and infrastructure. This situation drives coffee producers, particularly private coffee investors, to relocate to highlands. Although the highlands are suitable for coffee cultivation, there are social, economic, and environmental challenges. Moreover, land competition in highland areas is currently escalating. This catalyst allows coffee production to contribute to environmental degradation through deforestation. Nevertheless, there is concern that the current highlands will gradually change, thereby impacting future coffee production in the future [119, 120]. These effects, in turn, change weather conditions and progressively increase temperatures in highland areas. Similarly, the findings of [39] showed that climate change could shift the current coffee production areas to unsuitable areas without robust intervention mechanisms in Ethiopia and South Sudan. Climate change would also result in increased coffee production declines, altitudinal changes, threaten genetic diversity, and the extinction of wild Arabica coffee in Ethiopia [121]. Moreover, people are interested in migrating to highland areas; however, there is a restrictive land tenure system that makes it difficult for people to relocate, occupy, or own land. There is a risk that the demand for land in highland areas will cause social turmoil regarding resource use in the future. Additionally, the expansion of coffee growth is associated with the use of modern methods, which may also have a negative impact on indigenous knowledge. This supports the findings of [122], who found that as the landscape changes, industrialization occurs, and religious beliefs shift, indigenous knowledge becomes less viable. To address these problems, the policy of sustainable coffee production includes expansion of irrigation-supported coffee production, rehabilitation of land by planting trees, planting shade trees, using drought-resistant coffee varieties, and working on landslides and flood prevention. Besides, land expansion has become more complicated, exacerbating societal conflicts and accelerating deforestations especially in the highland areas. Overall, this study suggests that the government should develop new policies on land tenure systems and environmental conservation to solve these problems.

Our final finding revealed that climate change can affect two pillars of the global coffee supply chain: cultivation and logistics [123]. According to this study, climate change has a significant impact on the Ethiopian coffee value chain, particularly coffee processing, storage, and transportation, which are mostly dependent on traditional methods and pose significant hurdles for exporters. This factor makes it difficult for coffee growers to deliver quality coffee that meets the market needs. The main factors contributing to these effects were rainfall and temperature fluctuations. An increase in temperature can enhance fermentation, which can negatively affect the taste and flavour of coffee. Conversely, heavy rain causes coffee to fail to dry properly, making it susceptible to diseases, pests, and fungi. Although few farmers are involved in the proper drying and washing of coffee using traditional methods, they face great challenges in processing high-quality coffee. This study also showed that the coffee warehouse did not meet its standards or was equipped with modern technologies. Despite the use of certain methods, efforts by coffee processors to maintain coffee quality have been inadequate. Poor coffee storage stimulates the formation of Mycotoxins and Molds, which have a substantial impact on coffee quality. A previous study discovered that the cultivation, environment, storage conditions, fermentation, roasting, and brewing all have an impact on the quality of coffee beverages [124]. This indicates that climate change has an impact on the proliferation of microbial contaminations, which has a negative effect on both wet and dry coffee processing. A study in Ethiopia found that the growth of bacteria and fungi had a significant impact on the processing and storage of coffee beans [125]. Therefore, it is necessary to adopt modern storage facilities to increase the climate resilience of coffee plants. Our findings also illustrate the major impact of climate change on coffee transportation, emphasizing the importance of improving logistical resilience. Difficulties arise during hot or cold weather, rendering coffee exporters particularly vulnerable to their impacts; hence, a lack of technology during coffee transportation might reduce quality and market price [126]. This demonstrates that the interplay between climate change and the lack of modern equipment significantly affects the income of coffee producers and exporters. The study by [127] revealed that temperature and humidity fluctuations can significantly worsen the degradation of coffee quality. To address this issue, the coffee industry must provide modern machines and facilities for proper coffee processing, storage, and transportation, to enhance its market competitiveness. This further suggests that the coffee industry should take an innovative approach to improving coffee quality [128]. Moreover, while transporting coffee, it should be supported by climate-resistant equipment, refrigerated environment, infrastructure investment, and improved logistics to ensure resilience.

6. Limitation of the study

Although this study sheds light on the impact of climate change on the Ethiopian coffee value chain, it also acknowledges some limitations. First, the study used a cross-sectional research approach, focusing on specific season data, which may not accurately reflect long-term trends in climate variability and coffee production. Therefore, this research provides a foundation for future research on long-term trend data analysis. Second, the research focused on highland, midland, and lowland locations with diverse socio-economic, environmental, and climate-related factors. As a result, enumerators, especially females, faced significant challenges in collecting data from remote areas due to the dispersed population and inadequate infrastructure. Third, there were few people who declined interviews due to personal or political fear, resulting in their withdrawal from the interview. There were also participants who were not audio-recorded during the interview because of their restrictions related organization's confidentiality policies. Forth, we were sometimes challenged to realize the perceptions of farmers specially who lack adequate knowledge, experience and skills about the climate change and coffee production. Despite these limitations, using a mixed research technique provides a comprehensive understanding of the impact of climate change on coffee production, which poses challenges for the Ethiopian coffee value chain.

7. Conclusion

The economies of many countries, traders, and farmers heavily rely on Arabica coffee production. However, the sector is being threaten by climate change in multifaceted. We are thus motivated to study the climate change impact on Ethiopian Arabica coffee production and the challenges it poses to its value chain. We found that smallholder coffee farmers face challenges due to lack of average temperature and rainfall, affecting coffee planting season, flowering, and harvesting times, which reduce coffee beans' weight, size, and flavor, potentially impacting market demand. Climate change is causing coffee production decline, forcing farmers to shift to khat and commercial tree plantations for resilience, income, and lower costs, necessitating policy reforms and sustainable farming practices. The study also emphasizes the current prevalence of disease and insects, which have a detrimental impact on coffee production and quality. Despite the efforts of GOs, NGOs, and communities to date, it is imperative that urgent action be made to maintain sustainable coffee production. Climate change intensifies extreme weather events including landslides, floods, droughts, ice, and

frosts, which are significantly impacting coffee production and disrupting the coffee value chain. Climate change has also forced coffee to shift from lowland to highland areas. Although Ethiopia's highlands are suitable for coffee production issues such as increasing land competition, social conflicts, and environmental stresses have emerged. Climate change impacts coffee production, processing, storage, and transport, putting farmers at higher risk due to lack of effective mitigation strategies. The failure of coffee exporters to address climate change's effects at processing, storage, and transportation can lead to supply chain disruptions by reducing supply volume, reducing quality, and causing customer losses.

The overall impacts of climate change have led to the reduction of coffee yields, lower income, increased food insecurity, and perpetuation of the poverty cycle, necessitating the collaboration between communities, policymakers, and agricultural practitioners to improve the Ethiopian coffee industry's resilience in the future. Specifically, this study recommends policymakers strengthen collaborations among coffee farmers, cooperatives, private firms, government institutions, and NGOs for collaborative planning, information and knowledge sharing, and implementation of sustainable coffee production practices to enhance the coffee sector's resilience. The sustainable practices include shade trees, mulching, water conservation, water harvesting, drainage, irrigation, terracing, contour, improved coffee varieties, early warning system, and afforestation activities, etc. To ensure its implementation, it is necessary to provide capacity-building training for these coffee stakeholders on sustainable coffee cultivation practices. To reduce extreme weather events, it is especially important to collaborate closely with meteorological agencies, as they provide crucial early climate-related information. This can be achieved by fostering robust farmer-extension relationships, using digitalized extension services, and developing media infrastructure. In comparison to other agricultural activities, the coffee sector has received little attention in Ethiopia's national climate policies. This study thus recommends to policymakers that the coffee industry be given special attention in national climate policies such as Ethiopia's climate-resilience green economy, national adaptation strategy, environmental protection policy, and disaster risk management policy, among other things. Furthermore, it is important to support smallholder farmers by providing climate finance to capacitate them to effectively implement the adaptation and mitigation strategies and to diversify their sources of income during climate shocks. It is also crucial to support smallholder coffee farmers by providing climate finance to capacitate them to effectively implement adaptation and mitigation methods and diversify their sources of income during climate shocks. Finally, this study encourages academicians to conduct research on the paradoxical impact of climate change on coffee and khat production and marketing in the future.

Ethical statement

Ethics approval for this study was obtained from Jimma University's Ethics Committee. Accordingly, participants were informed about the study objectives, procedures, potential risks, participant confidentiality, data collection, and benefits, following institutional guidelines to ensure their rights. Research participants for surveys, interviews, and focus group discussions were contacted for data collection on the basis of their full consent. The survey and focus group discussions were mainly conducted with farmers, who were largely illiterate and could not read and write, so verbal consent was used. This also enabled participants to understand the study properly by providing oral explanations in their local language. In the cultural context, Ethiopian rural communities have more trust in oral than written documentation. Regarding the interviews, some participants provided written informed consent during the interviews, while verbal consent was used for those who were unwilling to do so. This is due to the fact that in the Ethiopian context, written consent associated with legal documentation often raises suspicion or discomfort.

Funding sources

This work was supported by Danida Fellowship Centre (No. 20-07-CBS).

Data availability statement

Data is accessible upon the reasonable request.

CRediT authorship contribution statement

Guta Regasa Megerssa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Weyessa Garedew:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kristjan Jespersen:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Janina Grabs:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Adugna Eneyew Bekele:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

No conflict of interest has been reported by the author(s).

References

[1] T. Watanabe, J. Cullmann, C.S. Pathak, M. Turunen, K. Emami, G. Ghinassi, et al., Management of climatic extremes with focus on floods and droughts in agriculture, Irrig. Drain 67 (2018) 29–42, https://doi.org/10.1002/ird.2204.
[2] R.Y.M. Kangalawe, C.G. Mung'ong'o, A.G. Mwakaje, E. Kalumanga, P.Z Yanda, Climate change and variability impacts on agricultural production and livelihood systems in Western Tanzania, Clim. Dev. 9 (2017) 202–216, https://doi.org/10.1080/17565529.2016.1146119.
[3] H. Azadi, A.A. Barati, Nooghabi S Nazari, J. Scheffran, Climate-related disasters and agricultural land conversion: towards prevention policies, Clim. Dev. 14 (2022) 814–828, https://doi.org/10.1080/17565529.2021.2008291.
[4] M.M.Q. Mirza, Climate change and extreme weather events: can developing countries adapt? Clim. Policy 3 (2003) 233–248, https://doi.org/10.3763/cpol.2003.0330.
[5] G. Parolini, Weather, climate, and agriculture: historical contributions and perspectives from agricultural meteorology, WIREs Clim. Change 13 (2022) e766, https://doi.org/10.1002/wcc.766.
[6] K. Afriyie, J.K. Ganle, E. Santos, The floods came and we lost everything': weather extremes and households' asset vulnerability and adaptation in rural Ghana, Clim. Dev. 10 (2018) 259–274, https://doi.org/10.1080/17565529.2017.1291403.
[7] J. Schmitt, F. Offermann, M. Söder, C. Frühauf, R. Finger, Extreme weather events cause significant crop yield losses at the farm level in German agriculture, Food Policy. 112 (2022) 102359, https://doi.org/10.1016/j.foodpol.2022.102359.
[8] G. Bussi, S.J. Dadson, C. Prudhomme, P.G. Whitehead, Modelling the future impacts of climate and land-use change on suspended sediment transport in the River Thames (UK), J. Hydrol. 542 (2016) 357–372, https://doi.org/10.1016/j.jhydrol.2016.09.010.
[9] R. Grotjahn, Weather extremes that affect various agricultural commodities, in: F. Castillo, M. Wehner, D.A. Stone (Eds.), Extreme Events Clim. Change, 1st ed., Wiley, 2021, pp. 21–48, https://doi.org/10.1002/9781119413738.ch3.
[10] J. Ali, T. Wahl, A.R. Enriquez, M.M. Rashid, J. Morim, M. Gall, et al., The role of compound climate and weather extreme events in creating socio-economic impacts in South Florida, Weather. Clim. Extrem. 42 (2023) 100625, https://doi.org/10.1016/j.wace.2023.100625.
[11] S. Mittnik, W. Semmler, A. Haider, Climate disaster risks—Empirics and a multi-phase dynamic model, Econometrics 8 (2020) 33, https://doi.org/10.3390/econometrics8030033.
[12] V. Panwar, S. Sen, Examining the economic impact of floods in selected Indian states, Clim. Dev. 12 (2020) 281–296, https://doi.org/10.1080/17565529.2019.1614897.
[13] M.K. Linnenluecke, A. Griffiths, M. Winn, Extreme weather events and the critical importance of anticipatory adaptation and organizational resilience in responding

to impacts, Bus. Strategy Env. 21 (2012) 17–32, https://doi.org/10.1002/bse.708.
[14] C. Lesk, P. Rowhani, N. Ramankutty, Influence of extreme weather disasters on global crop production, Nature 529 (2016) 84–87, https://doi.org/10.1038/nature16467.
[15] A. Ayanlade, A. Oluwaranti, O.S. Ayanlade, M. Borderon, H. Sterly, P. Sakdapolrak, et al., Extreme climate events in sub-Saharan Africa: a call for improving agricultural technology transfer to enhance adaptive capacity, Clim. Serv. 27 (2022) 100311, https://doi.org/10.1016/j.cliser.2022.100311.
[16] D. Beillouin, B. Schauberger, A. Bastos, P. Ciais, D. Makowski, Impact of extreme weather conditions on European crop production in 2018, Philos. Trans. R Soc. B Biol. Sci. 375 (2020) 20190510, https://doi.org/10.1098/rstb.2019.0510.
[17] A. Cogato, F. Meggio, Antoni De, M. Migliorati, F. Marinello, Extreme weather events in agriculture: a systematic review, Sustainability. 11 (2019) 2547, https://doi.org/10.3390/su11092547.
[18] M.G. Haile, T. Wossen, K. Tesfaye, J. Von Braun, Impact of climate change, weather extremes, and price risk on global food supply, Econ. Disasters Clim. Change 1 (2017) 55–75, https://doi.org/10.1007/s41885-017-0005-2.
[19] M.V.K. Sivakumar, Climate extremes and impacts on agriculture, editors, in: J. L. Hatfield, M.V.K. Sivakumar, J.H. Prueger (Eds.), Agron. Monogr, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Inc., Madison, WI, USA, 2018, pp. 621–647, https://doi.org/10.2134/agronmonogr60.2016.0003.
[20] T. Alcayna, I. Fletcher, R. Gibb, L. Tremblay, S. Funk, B. Rao, et al., Climate-sensitive disease outbreaks in the aftermath of extreme climatic events: a scoping review, One Earth. 5 (2022) 336–350, https://doi.org/10.1016/j.oneear.2022.03.011.
[21] N. Chhogyel, L. Kumar, Y. Bajgai, Consequences of climate change impacts and incidences of extreme weather events in relation to crop production in Bhutan, Sustainability. 12 (2020) 4319, https://doi.org/10.3390/su12104319.
[22] A. John, A.K. Riat, Bhat K Ahmad, S.A. Ganie, O. Endarto, C. Nugroho, et al., Adapting to climate extremes: implications for insect populations and sustainable solutions, J. Nat. Conserv. 79 (2024) 126602, https://doi.org/10.1016/j.jnc.2024.126602.
[23] M. Ziliotto, J.A.B. Chies, J.H. Ellwanger, Extreme weather events and pathogen pollution fuel infectious diseases: the 2024 flood-related leptospirosis outbreak in southern Brazil and other red lights, Pollutants 4 (2024) 424–433, https://doi.org/10.3390/pollutants4030028.
[24] S. Krishnan, Adaptive capacities for women's mobility during displacement after floods and riverbank erosion in Assam, India, Clim. Dev. 15 (2023) 404–417, https://doi.org/10.1080/17565529.2022.2092052.
[25] N. Marmai, Villoria M Franco, M. Guerzoni, How the Black Swan damages the harvest: extreme weather events and the fragility of agriculture in development countries, PLoS. One 17 (2022) e0261839, https://doi.org/10.1371/journal.pone.0261839.
[26] M. Ung, I. Luginaah, R. Chuenpagdee, G. Campbell, First-hand experience of extreme climate events and household energy conservation in coastal Cambodia, Clim. Dev. 10 (2018) 471–480, https://doi.org/10.1080/17565529.2017.1301865.
[27] R. Tito, H.L. Vasconcelos, K.J. Feeley, Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes, Glob. Change. Biol. 24 (2018), https://doi.org/10.1111/gcb.13959.
[28] S.I. Dupre, C.A. Harvey, M.B. Holland, The impact of coffee leaf rust on migration by smallholder coffee farmers in Guatemala, World Dev. 156 (2022) 105918, https://doi.org/10.1016/j.worlddev.2022.105918.
[29] D.P. Akinyi, S.K. Ng'ang'a, M. Ngigi, M. Mathenge, E. Girvetz, Cost-benefit analysis of prioritized climate-smart agricultural practices among smallholder farmers: evidence from selected value chains across sub-Saharan Africa, Heliyon. 8 (2022) e09228, https://doi.org/10.1016/j.heliyon.2022.e09228.
[30] A.A. Berhanu, Z.B. Ayele, D.C. Dagnew, A.B. Fenta, K.E. Kassie, Smallholder farmers' coping strategies to climate change and variability: evidence from Ethiopia, Clim. Serv. 35 (2024) 100509, https://doi.org/10.1016/j.cliser.2024.100509.
[31] R. Kombat, P. Sarfatti, O.A. Fatunbi, A review of climate-smart agriculture technology adoption by farming households in Sub-Saharan Africa, Sustainability. 13 (2021) 12130, https://doi.org/10.3390/su132112130.
[32] C. Makate, Effective scaling of climate smart agriculture innovations in African smallholder agriculture: a review of approaches, policy and institutional strategy needs, Env. Sci. Policy 96 (2019) 37–51, https://doi.org/10.1016/j.envsci.2019.01.014.
[33] R. Solomon, B. Simane, B.F. Zaitchik, The impact of climate change on agriculture production in Ethiopia: application of a dynamic computable General equilibrium model, Am. J. Clim. Change 10 (2021) 32–50, https://doi.org/10.4236/ajcc.2021.101003.
[34] P.C. Tanti, P.R. Jena, J.P. Aryal, D.B. Rahut, Role of institutional factors in climate-smart technology adoption in agriculture: evidence from an Eastern Indian state, Env. Chall. 7 (2022) 100498, https://doi.org/10.1016/j.envc.2022.100498.
[35] F.M. DaMatta, E. Rahn, P. Läderach, R. Ghini, J.C. Ramalho, Why could the coffee crop endure climate change and global warming to a greater extent than previously estimated? Clim. Change 152 (2019) 167–178, https://doi.org/10.1007/s10584-018-2346-4.
[36] G. Hochachka, Climate change and the transformative potential of value chains, Ecol. Econ. 206 (2023) 107747, https://doi.org/10.1016/j.ecolecon.2023.107747.
[37] F.B. Chalchissa, G.M. Diga, G.L. Feyisa, A.R. Tolossa, Impacts of extreme agroclimatic indicators on the performance of coffee (Coffea arabica L.) aboveground biomass in Jimma Zone, Ethiopia, Heliyon. 8 (2022) e10136, https://doi.org/10.1016/j.heliyon.2022.e10136.
[38] A. Chemura, B.T. Mudereri, A.W. Yalew, C. Gornott, Climate change and specialty coffee potential in Ethiopia, Sci. Rep. 11 (2021) 8097, https://doi.org/10.1038/s41598-021-87647-4.
[39] J. Moat, J. Williams, S. Baena, T. Wilkinson, T.W. Gole, Z.K. Challa, et al., Resilience potential of the Ethiopian coffee sector under climate change, Nat. Plants 3 (2017) 17081, https://doi.org/10.1038/nplants.2017.81.
[40] CSA. Agricultural Sample Survey 2019-20. Volume I: Report on Area and Production of Major Crops (Private Peasant Holdings, Meher Season). Statistical Bulletin No. 587, Addis Ababa. 2020.
[41] B. Minten, T. Assefa, K. Hirvonen, Can agricultural traders be trusted? Evidence from coffee in Ethiopia, World Dev. 90 (2017) 77–88, https://doi.org/10.1016/j.worlddev.2016.08.018.
[42] S.K. Hundie, B. Biratu, Response of Ethiopian coffee price to the world coffee price: evidence from dynamic ARDL simulations and nonlinear ARDL cointegration, Cogent. Econ. Finance 10 (2022) 2114168, https://doi.org/10.1080/23322039.2022.2114168.
[43] B. Minten, M. Dereje, E. Engida, T. Kuma, Coffee value chains on the move: evidence in Ethiopia, Food Policy 83 (2019) 370–383, https://doi.org/10.1016/j.foodpol.2017.07.012.
[44] C. Bunn, P. Läderach, O.O. Rivera, D. Kirschke, A bitter cup: climate change profile of global production of Arabica and Robusta coffee, Clim. Change 129 (2015) 89–101, https://doi.org/10.1007/s10584-014-1306-x.
[45] A.C.W. Craparo, P.J.A. Van Asten, P. Läderach, L.T.P. Jassogne, S.W. Grab, Coffea arabica yields decline in Tanzania due to climate change: global implications, Agric. For. Meteorol. 207 (2015) 1–10, https://doi.org/10.1016/j.agrformet.2015.03.005.
[46] D.B. Ebisa, Impacts of climate change on global coffee production industry: review, Afr. J. Agric. Res. 12 (2017) 1607–1611, https://doi.org/10.5897/AJAR2017.12147.
[47] IPCC. Climate Change 2014, Synth. Rep. (2014).
[48] M. Baca, P. Läderach, J. Haggar, G. Schroth, O. Ovalle, An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in Mesoamerica, PLoS One 9 (2014) e88463, https://doi.org/10.1371/journal.pone.0088463.
[49] C. Gay, F. Estrada, C. Conde, H. Eakin, L. Villers, Potential impacts of climate change on agriculture: a case of study of coffee production in Veracruz, Mexico, Clim. Change 79 (2006) 259–288, https://doi.org/10.1007/s10584-006-9066-x.
[50] M. Hirons, E. Beauchamp, S. Whitfield, D. Conway, R. Asare, Y. Malhi, Resilience to climate shocks in the tropics, Env. Res. Lett. 15 (2020) 100203, https://doi.org/10.1088/1748-9326/abb156.
[51] J. Jaramillo, E. Muchugu, F.E. Vega, A. Davis, C. Borgemeister, A. Chabi-Olaye, Some like it hot: the influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa, PLoS One 6 (2011) e24528, https://doi.org/10.1371/journal.pone.0024528.
[52] P. Laderach, M. Lundy, A. Jarvis, J. Ramirez, E.P. Portilla, K. Schepp, et al., Predicted impact of climate change on coffee supply chains, In:. Filho WL, editor. Econ. Soc. Polit. Elem. Clim. Change, Springer Berlin Heidelberg, Berlin, Heidelberg, 2011, pp. 703–723, https://doi.org/10.1007/978-3-642-14776-0_42.
[53] B.O. Abidoye, A.F. Odusola, Climate change and economic growth in Africa: an econometric analysis, J. Afr. Econ. 24 (2015) 277–301, https://doi.org/10.1093/jae/eju033.
[54] P. Alagidede, G. Adu, P.B. Frimpong, The effect of climate change on economic growth: evidence from Sub-Saharan Africa, Env. Econ. Policy Stud. 18 (2016) 417–436, https://doi.org/10.1007/s10018-015-0116-3.
[55] A. Rezai, L. Taylor, D. Foley, Economic growth, income distribution, and climate change, Ecol. Econ. 146 (2018) 164–172, https://doi.org/10.1016/j.ecolecon.2017.10.020.
[56] A.F. Salad, S. Zziwa, D. Talengera, Lydia Nabatanzi, Olivia Makumbi, Vivian Najjuma, et al., Adoption intensity of climate smart agricultural practices in arabica coffee production in Bududa District, Int. J. Multidiscip. Res. Updat. 1 (2021) 016–025, https://doi.org/10.53430/ijmru.2021.1.1.0037.
[57] S. Diro, A. Tesfaye, B. Erko, Determinants of adoption of climate-smart agricultural technologies and practices in the coffee-based farming system of Ethiopia, Agric. Food Secur. 11 (2022) 42, https://doi.org/10.1186/s40066-022-00385-2.
[58] V.D. Nguyen, T.C. Pham, T.T. Pham, A.N. Phan, Digital and circular technologies for climate-smart and sustainable agriculture: the case of Vietnamese coffee, IOP. Conf. Ser. Earth. Env. Sci. 1278 (2023) 012003, https://doi.org/10.1088/1755-1315/1278/1/012003.
[59] P.G. Schmidt, C. Bunn, Coordinated implementation of climate-smart practices in coffee farming increases benefits at farm, landscape and global scale, Front. Clim. 3 (2021) 746139, https://doi.org/10.3389/fclim.2021.746139.
[60] S. Wulandari, F. Djufry, R.S. Hartati, Agricultural innovation system development to support environmental management implementation in coffee smallholder plantation, IOP. Conf. Ser. Earth. Env. Sci 950 (2022) 012065, https://doi.org/10.1088/1755-1315/950/1/012065.
[61] Y. Pham, K. Reardon-Smith, S. Mushtaq, G. Cockfield, The impact of climate change and variability on coffee production: a systematic review, Clim. Change 156 (2019) 609–630, https://doi.org/10.1007/s10584-019-02538-y.
[62] O. Ovalle-Rivera, P. Läderach, C. Bunn, M. Obersteiner, G. Schroth, Projected shifts in coffea arabica suitability among major global producing regions due to

climate change, PLoS One 10 (2015) e0124155, https://doi.org/10.1371/journal.pone.0124155.
[63] J. Zullo, H.S. Pinto, E.D. Assad, A.M.H De Ávila, Potential for growing Arabica coffee in the extreme south of Brazil in a warmer world, Clim. Change 109 (2011) 535–548, https://doi.org/10.1007/s10584-011-0058-0.
[64] G. Schroth, P. Laderach, J. Dempewolf, S. Philpott, J. Haggar, H. Eakin, et al., Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mex. Mitig. Adapt. Strateg. Glob. Change 14 (2009) 605–625, https://doi.org/10.1007/s11027-009-9186-5.
[65] T. Chaichana, G. Reeve, P. Piboonrungroj, J. Muangprathub, J. Kunno, M. G. Robson, et al., Data from a survey of coffee cultivation in lowland and highland areas to support agriculture during climate change, Data Br. 56 (2024) 110881, https://doi.org/10.1016/j.dib.2024.110881.
[66] F. Ceballos-Sierra, S. Dall'Erba, The effect of climate variability on Colombian coffee productivity: a dynamic panel model approach, Agric. Syst. 190 (2021) 103126, https://doi.org/10.1016/j.agsy.2021.103126.
[67] Dekens J., Bagamba F. Climate resilient value chains and food systems: promoting an integrated approach to Climate adaptation: lessons from the coffee value chain in Uganda 2014.
[68] Kara M Er, A. Ghadge, U.S Bititci, Modelling the impact of climate change risk on supply chain performance, Int. J. Prod. Res. 59 (2021) 7317–7335, https://doi.org/10.1080/00207543.2020.1849844.
[69] K. Katsaliaki, P. Galetsi, S. Kumar, Supply chain disruptions and resilience: a major review and future research agenda, Ann. Oper. Res. 319 (2022) 965–1002, https://doi.org/10.1007/s10479-020-03912-1.
[70] N.Y. Yun, M.A. Ülkü, Sustainable supply chain risk management in a climate-changed world: review of extant literature, trend analysis, and guiding framework for future research, Sustainability 15 (2023) 13199, https://doi.org/10.3390/su151713199.
[71] ICO I.C.O. Historical data on the global coffee trade., 2015.
[72] M.M. Urugo, M. Worku, Y.B. Tola, H.F. Gemede, Ethiopian coffee: production systems, geographical origin traceability, and European Union deforestation regulation directive compliance, J. Agric. Food Res. 19 (2025) 101695, https://doi.org/10.1016/j.jafr.2025.101695.
[73] A. Adane, Analysis of stakeholders' roles and interactions in quality coffee production: implications for sustainable land management in Yirgacheffe, Southern Ethiopia, Environ. Dev. Sustain. (2023), https://doi.org/10.1007/s10668-023-03140-0.
[74] Minten B., Tamru S., Kuma T., Nyarko Y. Structure and performance of Ethiopia's coffee export sector 2014.
[75] N. Petit, Ethiopia's coffee sector: a bitter or better future? J. Agrar. Change 7 (2007) 225–263, https://doi.org/10.1111/j.1471-0366.2007.00145.x.
[76] A.M. Aparis, Ethiopian Coffee Marketing Reforms and Smallholder Coffee Producers: A Socio-Legal Empowerment Lens, IIED, London, 2021.
[77] S. Tamru, B. Minten, J. Swinnen, Trade, value chains, and rent distribution with foreign exchange controls: coffee exports in Ethiopia, Agric. Econ. 52 (2021) 81–95, https://doi.org/10.1111/agec.12608.
[78] Tefera A., Tefera T. Coffee Annual Report: USDA Foreign Agricultural Service. 2014.
[79] G. Addisie, L. Tebarek, Upgrading opportunities and challenges for small coffee producers in Sidama Region of Ethiopia, Int. J. Rural Manag. 19 (2023) 234–252, https://doi.org/10.1177/09730052221080884.
[80] A.A. Amamo, Coffee production and marketing in Ethiopia, Eur. J. Bus. Manag. 6 (37) (2014).
[81] B. Tadesse, Y. Tilahun, T. Bekele, G. Mekonen, Assessment of challenges of crop production and marketing in Bench-Sheko, Kaffa, Sheka, and West-Omo zones of southwest Ethiopia, Heliyon 7 (2021) e07319, https://doi.org/10.1016/j.heliyon.2021.e07319.
[82] T. Duguma, Value chain analysis of Ethiopian coffee (Coffea arabica), Arch. Curr. Res. Int. 11 (2017) 1–15, https://doi.org/10.9734/ACRI/2017/31486.
[83] Gashaw B.A., Habteyesus D.G., Nedjo Z.S. Value chain analysis of coffee in Jimma Zone of Oromia Regional State, Ethiopia 2018.
[84] N. Gashaye, M. Binganidzo, Institutional actors and their impact on postharvest coffee value chain performance in Ethiopia, J. Agribus. Rural Dev. 70 (2023) 445–456, https://doi.org/10.17306/J.JARD.2023.01780.
[85] S. Tolesa, B. Tolesa, An examination of Ethiopian data on the coffee value chain from a systemic perspective, Int. J. Bus. Econ. Res. 13 (2024) 142–151, https://doi.org/10.11648/j.ijber.20241306.11.
[86] J.M. Brinkerhoff, Agency in institutional reform: creating the Ethiopia Commodities Exchange, Public Adm. Dev. 35 (2015) 301–314, https://doi.org/10.1002/pad.1732.
[87] F. Mitiku, Y. De Mey, J. Nyssen, M. Maertens, Do private sustainability standards contribute to income growth and poverty alleviation? A comparison of different coffee certification schemes in Ethiopia, Sustainability 9 (2017) 246, https://doi.org/10.3390/su9020246.
[88] B. Saunders, J. Sim, T. Kingstone, S. Baker, J. Waterfield, B. Bartlam, et al., Saturation in qualitative research: exploring its conceptualization and operationalization, Qual. Quant. 52 (2018) 1893–1907, https://doi.org/10.1007/s11135-017-0574-8.
[89] Walker S., Y.G./E. Getahun, K. Tesfaye, G. Mamo, A. Yeshanew, E. Bekele. The use of agroclimatic zones AS a basis for tailored seasonal rainfall forecasts for The cropping systems in The Central Rift Valley of Ethiopia 2003. https://doi.org/10.13140/2.1.1709.1522.
[90] A.S. Das, KoboToolbox. Open Electron. Data capture tools med. Biomed. Res. Med. Allied Prof., Elsevier, 2024, pp. 241–329, https://doi.org/10.1016/B978-0-443-15665-6.00004-X.
[91] M. Naderifar, H. Goli, F. Ghaljaie, Snowball sampling: a purposeful method of sampling in qualitative research, Strides Dev. Med. Educ. 14 (2017), https://doi.org/10.5812/sdme.67670.
[92] J. Kirchherr, K. Charles, Enhancing the sample diversity of snowball samples: recommendations from a research project on anti-dam movements in Southeast Asia, PLoS One 13 (2018) e0201710, https://doi.org/10.1371/journal.pone.0201710.
[93] M. Mamuye, C. Gallemore, K. Jespersen, N. Kasongi, G. Berecha, Changing rainfall and temperature trends and variability at different spatiotemporal scales threaten coffee production in certain elevations, Env. Chall. 15 (2024) 100950, https://doi.org/10.1016/j.envc.2024.100950.
[94] S. Wagner, L. Jassogne, E. Price, M. Jones, R. Preziosi, Impact of climate change on the production of coffea arabica at Mt. Kilimanjaro, Tanzania, Agriculture 11 (2021) 53, https://doi.org/10.3390/agriculture11010053.
[95] J.A. Lorençone, P.A. Lorençone, L.E.O. Aparecido, G.B. Torsoni, L.D.R. Ferreira, Impact of climate change on the suitability of coffea arabica cultivation in Brazil in the period 2040-2080, Rev. Contemp. 3 (10) (2023) 17811–17821, https://doi.org/10.56083/RCV3N10-063.
[96] W.P. Ferreira, J.I. Ribeiro Júnior, C. De Fátima Souza, Climate change does not impact on *coffea arabica* yield in Brazil, J. Sci. Food Agric. 99 (2019) 5270–5282, https://doi.org/10.1002/jsfa.8465.
[97] L. Wang, Y. Li, J. Wu, Z. An, L. Suo, J. Ding, et al., Effects of the rainfall intensity and slope gradient on soil erosion and nitrogen loss on the sloping fields of Miyun reservoir, Plants 12 (2023) 423, https://doi.org/10.3390/plants12030423.
[98] Y. Yao, Q. Dai, R. Gao, Y. Gan, X. Yi, Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China, PLoS One 16 (2021) e0246505, https://doi.org/10.1371/journal.pone.0246505.
[99] L. Zhao, Q. Fang, R. Hou, F. Wu, Effect of rainfall intensity and duration on soil erosion on slopes with different microrelief patterns, Geoderma 396 (2021) 115085, https://doi.org/10.1016/j.geoderma.2021.115085.
[100] D. Groenen, The effects of climate change on the pests and diseases of coffee crops in Mesoamerica, J. Clim. Weather Forecast 06 (2018), https://doi.org/10.4172/2332-2594.1000239.
[101] B.J.A. Mouen, C. Cilas, J.L. Nottéghem, D. Bieysse, Effect of temperatures and rainfall variations on the development of coffee berry disease caused by Colletotrichum kahawae, Crop. Prot. 31 (2012) 125–131, https://doi.org/10.1016/j.cropro.2011.09.010.
[102] Z. Guido, C. Knudson, T. Finan, M. Madajewicz, K. Rhiney, Shocks and cherries: the production of vulnerability among smallholder coffee farmers in Jamaica, World Dev. 132 (2020) 104979.
[103] L. Cochrane, D. O'Regan, Legal harvest and illegal trade: trends, challenges, and options in khat production in Ethiopia, Int. J. Drug Policy 30 (2016) 27–34, https://doi.org/10.1016/j.drugpo.2016.02.009.
[104] E. Gebissa, Scourge of life or an economic lifeline? Public discourses on Khat (*Catha edulis*) in Ethiopia, Subst. Use Misuse 43 (2008) 784–802, https://doi.org/10.1080/10826080701738950.
[105] Y.Z. Hussein, B.A. Wondimagegnhu, G.S. Misganaw, The effect of khat cultivation on rural households' income in Bahir Dar Zuria District, Northwest Ethiopia, GeoJournal 88 (2022) 1369–1388, https://doi.org/10.1007/s10708-022-10697-2.
[106] D.A. Tofu, K. Wolka, Climate change induced a progressive shift of livelihood from cereal towards Khat (Chata edulis) production in eastern Ethiopia, Heliyon 9 (2023) e12790, https://doi.org/10.1016/j.heliyon.2022.e12790.
[107] K. Habtamu, S. Teferra, A. Mihretu, Exploring the perception of key stakeholders toward khat policy approaches in Ethiopia: a qualitative study, Harm. Reduct. J. 20 (2023) 115, https://doi.org/10.1186/s12954-023-00858-y.
[108] M. Wuletaw, Public discourse on Khat (Catha edulis) production in Ethiopia: review, J. Agric. Ext. Rural Dev. 10 (2018) 192–201, https://doi.org/10.5897/JAERD2018.0984.
[109] G. Ermansons, UK khat prohibition and the making of a harmful drug, Med. Anthr. Theory 11 (2024) 1–29, https://doi.org/10.17157/mat.11.3.7292.
[110] P. Griffiths, D. Lopez, R. Sedefov, A. Gallegos, B. Hughes, A. Noor, et al., Khat use and monitoring drug use in Europe: the current situation and issues for the future, J. Ethnopharmacol. 132 (2010) 578–583, https://doi.org/10.1016/j.jep.2010.04.046.
[111] S. Kassim, A. Dalsania, J. Nordgren, A. Klein, J. Hulbert, Before the ban - an exploratory study of a local khat market in East London, U.K, Harm. Reduct. J. 12 (2015) 19, https://doi.org/10.1186/s12954-015-0048-z.
[112] C.W. Fraisse, N. Guindin-Garcia, M.Z. Karrei, V.A. Cerbaro, A.T. Lazzaretti, CIFA: a roadmap for services to monitor weather extremes affecting agriculture under a changing climate, Clim. Serv. 35 (2024) 100506, https://doi.org/10.1016/j.cliser.2024.100506.
[113] E. Njuki, N.J. Nava, B.E Bravo-Ureta, Climate and weather impacts on agricultural productivity. Ref. Module Earth Syst. Env. Sci., Elsevier, 2024 B9780323910132000290, https://doi.org/10.1016/B978-0-323-91013-2.00029-0.
[114] J. Bucheli, N. Conrad, S. Wimmer, T. Dalhaus, R. Finger, Weather insurance in European crop and horticulture production, Clim. Risk. Manage. 41 (2023) 100525, https://doi.org/10.1016/j.crm.2023.100525.
[115] F.G. Santeramo, E. Lamonaca, I. Maccarone, M. Tappi, Extreme weather events and crop insurance demand, Heliyon 10 (2024) e27839, https://doi.org/10.1016/j.heliyon.2024.e27839.
[116] P. Shirsath, S. Vyas, P. Aggarwal, K.N. Rao, Designing weather index insurance of crops for the increased satisfaction of farmers, industry and the government, Clim. Risk. Manage. 25 (2019) 100189, https://doi.org/10.1016/j.crm.2019.100189.

[117] N. Sinnarong, S. Kuson, W. Nunthasen, S. Puphoung, V. Souvannasouk, The potential risks of climate change and weather index insurance scheme for Thailand's economic crop production, Env. Chall. 8 (2022) 100575, https://doi.org/10.1016/j.envc.2022.100575.
[118] N.E. Benti, G.S. Gurmesa, T. Argaw, A.B. Aneseyee, S. Gunta, G.B. Kassahun, et al., The current status, challenges and prospects of using biomass energy in Ethiopia, Biotechnol. Biofuels 14 (2021) 209, https://doi.org/10.1186/s13068-021-02060-3.
[119] C.T. Cassamo, D. Draper, M.M. Romeiras, I. Marques, R. Chiulele, M. Rodrigues, et al., Impact of climate changes in the suitable areas for Coffea arabica L. production in Mozambique: agroforestry as an alternative management system to strengthen crop sustainability, Agric. Ecosyst. Env. 346 (2023) 108341, https://doi.org/10.1016/j.agee.2022.108341.
[120] S.G. Mbwambo, S.K. Mourice, A.J.P. Tarimo, The impacts of current climate variability on coffee production in the Northern and southern highlands of Tanzania, J. Agric. Sci. 14 (2022) 78, https://doi.org/10.5539/jas.v14n3p78.
[121] A.P. Davis, T.W. Gole, S. Baena, J. Moat, The impact of climate change on indigenous Arabica coffee (Coffea arabica): predicting future trends and identifying priorities, PLoS One 7 (2012) e47981, https://doi.org/10.1371/journal.pone.0047981.
[122] E. Nyadzi, O.C. Ajayi, F. Ludwig, Indigenous knowledge and climate change adaptation in Africa: a systematic review, CABI Rev. (2021) PAVSNNR202116029, https://doi.org/10.1079/PAVSNNR202116029.
[123] R. Zhou, Y. Wang, M. Jin, J. Mao, X. Zheng, Coffee supply chain planning under climate change, J. Integr. Env. Sci. 19 (2022) 1–15, https://doi.org/10.1080/1943815X.2022.2103570.
[124] F. Bastian, O.S. Hutabarat, A. Dirpan, F. Nainu, H. Harapan, T.B. Emran, et al., From plantation to cup: changes in bioactive compounds during coffee processing, Foods 10 (2021) 2827, https://doi.org/10.3390/foods10112827.
[125] S.W. Abaya, M. Bråtveit, W. Deressa, A. Kumie, A. Tenna, B.E. Moen, Microbial contamination of coffee during postharvest on farm processing: a concern for the respiratory health of production workers, Arch. Env. Occup. Health 75 (2020) 201–208, https://doi.org/10.1080/19338244.2019.1592094.
[126] M.J. Koetse, P. Rietveld, The impact of climate change and weather on transport: an overview of empirical findings, Transp. Res. Part Transp. Env. 14 (2009) 205–221, https://doi.org/10.1016/j.trd.2008.12.004.
[127] G.C. Matias, A.P.D.C. Alves, F.M. Borem, L. Haeberlin, C.M.D. Santos, S.D.V.F. D. Rosa, Effect of storage conditions on the physical properties of coffee beans with different qualities, EUREKA Life Sci. (2023) 35–49, https://doi.org/10.21303/2504-5695.2023.003008.
[128] G.V.D.M. Pereira, V. De Mello Sampaio, N. Wiele, A. Da Silva Vale, D.P. De Carvalho Neto, A.D.F.D.D. Souza, et al., How yeast has transformed the coffee market by creating new flavors and aromas through modern post-harvest fermentation systems, Trends. Food Sci. Technol. 151 (2024) 104641, https://doi.org/10.1016/j.tifs.2024.104641.