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Review Paper

How does climate change affect biomass production and rural poverty?

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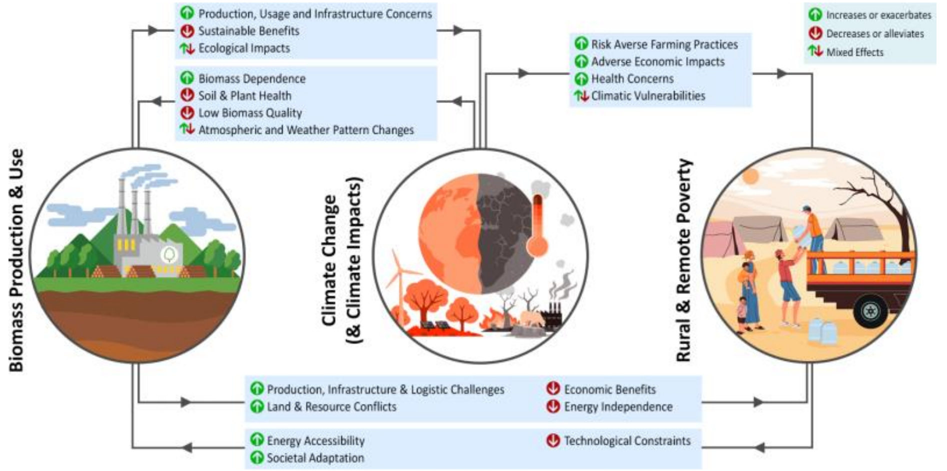
HIGHLIGHTS

- ➢Climate change and biomass production have a complex bi-directional relationship.
- ➢Climate change exacerbates vulnerability to poverty in rural/remote communities.
- ➢Chain reactions exist between rural poverty, biomass production, and climate change.
- ➢Sustainable bioenergy may support economic development and environmental health.
- ➢Community-specific sustainable biofuel solutions should balance food-fuel needs.

GRAPHICAL ABSTRACT



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ABSTRACT

The interrelation between climate change, biomass production, and rural poverty is an area of growing concern, as these factors are intricately linked and often exacerbate one another. The objective of this critical review is to investigate existing knowledge, identify research gaps, and explore how climate-induced disruptions affect biomass production, exacerbate rural poverty, and increase vulnerability. High-quality peer-review publications were sourced *via* Web of Science, Scopus, and Google Scholar to include the most relevant papers in line with the objective. A bibliometric analysis yielded three key concepts: (i) biofuel innovations and sustainable development, (ii) climate dynamics and biomass environmental impact, and (iii) rural poverty and energy challenges. The review delves into the complex interplay of factors influencing biomass production, climate change, and rural/remote poverty. Climate change intensifies the challenges rural communities face, enhancing their vulnerability to poverty. For these communities, biomass production not only offers a sustainable energy alternative but also a pathway to economic upliftment. Addressing climate change through sustainable biomass production emerges as a vital strategy, providing a dual solution by mitigating environmental degradation and offering a robust framework for poverty alleviation in rural areas. The review emphasizes the urgent need to integrate climate action, sustainable energy production, and rural economic development.

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Abbreviations

BDH	Biomass district heating
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary disease
CRISPR	Clustered regularly interspaced short palindromic repeats
GHG(s)	Greenhouse gas(es)
FACE	Free-Air Carbon Dioxide Enrichment
IDMC	Internal Displacement Monitoring Centre
SOC	Soil organic carbon

1. Introduction

Climate change is one of the most pressing global challenges of our time, with far-reaching consequences extending beyond environmental science to encompass socioeconomic and human welfare aspects (Watson et al., 2005; Louis and Hess, 2008; Hasegawa et al., 2016). It is a phenomenon driven primarily by the emission of greenhouse gases (GHGs) into the atmosphere, leading to rising temperatures, altered weather patterns, and increased frequency of extreme events (IPCC, 2014 and 2018). This anthropogenic influence on the Earth's climate system has drawn significant attention due to its wide-ranging implications for ecosystems, economies, and communities across the globe (IPCC, 2014 and 2018).

In recent years, the nexus between climate change, biomass production, and rural/remote poverty has emerged as a critical area of concern and investigation (Kishore et al., 2004; Sharma et al., 2016). Biomass production, the cultivation of organic materials such as crops, forests, and livestock, is a cornerstone of rural livelihoods, providing sustenance, energy, and income for millions of people worldwide (Miah et al., 2010; Wu et al., 2019; Lozano et al., 2023). The importance of biomass production in rural areas extends to its role in meeting essential needs for food security (Mirzabaev et al., 2018; Schuenemann et al., 2018), energy access, and overall economic well-being (Zheng et al., 2010; Mohammed et al., 2013; Mirzabaev et al., 2018). Within these rural landscapes, a substantial proportion of the world's population resides (Macrotrends, 2023), and many communities are highly dependent on the productivity of their natural resources.

Simultaneously, rural poverty represents an enduring global challenge, persisting despite advancements in urbanization and economic development (Jensen et al., 2003; Dercon, 2009). Rural poverty manifests as food insecurity, inadequate healthcare, lack of education, and limited income-generating opportunities, thus perpetuating a cycle of vulnerability for those living in these regions (International Fund for Agricultural Development, 2010). Climate change and climatic variability are widely acknowledged as factors that can intensify vulnerability to poverty, especially in regions with high poverty levels (Leichenko and Silva, 2014). Vulnerable populations often rely heavily on activities like agriculture that are acutely susceptible to shifts in temperature and precipitation patterns, leading to challenges like loss of income, hunger, adverse health effects, and displacement (IPCC, 2018). According to the Internal Displacement Monitoring Centre (IDMC), weather-related disasters, including droughts

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and floods, led to 30.7 million new internal displacements across 145 countries and territories in 2020 (Internal Displacement Monitoring Centre, 2021). Furthermore, extreme events, such as droughts, floods, and heatwaves, particularly when consecutive, can further deplete the resources and livelihoods of impoverished rural populations, affecting labor efficiency, housing stability, infrastructure, and social networks (Olsson et al., 2014).

The interrelation between climate change, biomass production, and rural poverty is an area of growing concern, as these factors are intricately linked and often exacerbate one another. In 2017, human activities had raised temperatures by about 1°C above levels seen before the industrial era, with an ongoing increase of 0.2°C every ten years. This temperature rise has led to significant changes in both human and environmental systems. There has been a surge in events like droughts, floods, and other extreme weather conditions, along with rising sea levels and diminishing biodiversity, posing unique threats to those most vulnerable (IPCC, 2014; Mysiak et al., 2016). Climate change-induced disruptions, such as altered rainfall patterns, more frequent and severe droughts, and increased temperatures, directly impact agricultural productivity in rural areas, leading to reduced crop yields and increased livestock stress (IPCC, 2014). These changes, in turn, undermine food security and income sources, intensifying rural poverty and heightening vulnerability (Wheeler and Von Braun, 2013).

In this review, our primary goal is to examine the intricate relationships between climate change, biomass production in rural/remote areas, and their impact on rural/remote poverty. We will assess the existing knowledge, identify research gaps, and explore how climate-induced disruptions affect biomass production, exacerbate rural/remote poverty, and heighten vulnerability. By synthesizing the available literature, we aim to emphasize the critical importance of addressing these interconnected issues and advocate for effective policies and sustainable strategies to mitigate the challenges rural communities face in the context of climate change. **Table 1** outlines key research on the interconnections between climate change, biomass production, and poverty in rural and remote areas, compiled to highlight the novelty of the current study. To the best of our knowledge, this is the first study that investigates the nexus between climate change, biomass production, and rural/remote poverty.

2. Materials and Methods

2.1. Literature screening

Peer-reviewed publications were identified using Scopus, Web of Science, and Google Scholar to source journal articles on the intersections of "biomass production and climate change", "climate change and rural poverty", and "biomass production and rural poverty". For this review, we focused solely on literature published in English and accessible online. The most relevant papers in line with the study's objectives were selected. Additionally, reference checking was conducted on the selected articles to further ensure comprehensive coverage. The step-by-step process we undertook during our literature search and selection is illustrated in the flowchart presented in **Figure 1**. While this review does not encompass all available literature on the topic, we aimed to highlight key concepts and incorporate high-quality, recent publications.

2.2. Bibliometric analysis

Bibliometric analyses are becoming a common research tool used in different areas of science to support the analysis of large volumes of scientific literature and produce a high-value summary (Van Eck and Waltman, 2010; Donthu et al., 2021). A bibliometric evaluation of the titles and abstracts in the relevant literature was completed to understand the trends in the research field. VOSviewer software (version 1.6.19) was employed to conduct the analysis (Van Eck and Waltman, 2010). A map was developed based on the co-occurrence of text data, utilizing the full counting method with a minimum of 10 occurrences of a term and a relevance score of 60%. Terms that did not add value to the figure, such as article structure terms (i.e., introduction, methods, context, article, use, hand, increase), were excluded. **Figure 2** presents the results of the analysis and the three concept clusters that were produced: Biofuel Innovations and Sustainable Development (Cluster 1), Climate Dynamics and Biomass Environmental Impact (Cluster 2), and Rural Poverty and Energy Challenges (Cluster 3).

3. Literature Review

3.1. Climate change and biomass production

Biomass production and climate change are interconnected, and their effect is bi-directional. Climate variations can influence biomass production, leading to a range of beneficial and detrimental outcomes. Conversely, biomass practices can impact the climate ecosystem. In this review, the bi-directional relationship is structured as follows: (i) the effects of climate change on biomass resources and/or yield, (ii) the impact of climate change on the production and utilization of biomass energy, and (iii) the environmental consequences of biomass energy production.

3.1.1. Effects of climate change on biomass resources and/or yield

Various climate elements, such as temperature, precipitation, air moisture, and CO_2 levels, play significant roles in determining plant biomass production (Flanagan and Johnson, 2005; Kardol et al., 2010). Each plant species has a designated minimum, maximum, and optimal range for these factors, achieving peak biomass production within these optimal values. Any deviations from these ranges can negatively impact the biomass production rate (Hatfield et al., 2011; Hatfield and Prueger, 2015). Climate change generally influences temperature, rainfall patterns, CO_2 concentrations, air moisture, and water availability, all of which directly or indirectly affect biomass growth and productivity (Freitas et al., 2021; Larjavaara et al., 2021). The mechanisms by which these climate factors impact biomass production are discussed below.

3.1.1.1. Temperature's dual role in biomass production

One of the primary climate factors influencing plant growth and development is temperature. The rate of plant development accelerates as temperatures rise to a species' optimum level (Hatfield and Prueger, 2015). However, the effects of increasing temperatures on biomass production can vary based on geographical region and plant species (Maracchi et al., 2005). For instance, global warming may enhance agricultural and forest yields in temperate zones. Colder temperatures and shorter growing seasons currently limit agricultural and forest productivity in temperate zones. With warmer and shorter winters combined with elevated CO_2 levels, global warming could extend the growth season in temperate zones. This could allow for longer cultivation periods and potentially result in higher biomass yields (Wang et al., 2021).

Conversely, increased temperatures might negatively impact plant development in the tropics and sub-tropics. A physiological model-based study showed that the above-ground biomass of old-growth forests is expected to decrease by 41% in the tropics and by 29% globally due to rising temperatures in the future (Larjavaara et al., 2021). Tropical and sub-tropical regions already experience long, hot summers and brief, mild winters. An intensification of warm temperatures could exceed the maximum temperature range tolerable for many crops and plants (Seneviratne et al., 2002). In such environments, a higher plant and crop mortality rate is anticipated, as extreme temperatures could disrupt the metabolic and physiological activities of plants (Bita and Gerats, 2013). For example, functions like photosynthesis and transpiration could be permanently compromised in extremely high temperatures (Mathur et al., 2014). Rising temperatures beyond optimum levels can also impair water and nutrient uptake (Kreuzwieser and Gessler, 2010). Moreover, rising temperatures are predicted to cause a shift in climate zones, which may alter the distribution and abundance of plants (Rubenstein et al., 2023).

3.1.1.2. Atmospheric CO_2 levels and biomass production

The concentration of CO_2 in the atmosphere is on the rise. Anthropogenic factors, such as unchecked industrial emissions, are responsible for the rising concentrations of CO_2 in the atmosphere. While CO_2 is a recognized GHG that contributes to global warming, elevated concentrations of CO_2 significantly affect plant growth through its impact on photosynthesis, water uptake, respiration, and carbon availability. Higher CO_2 concentrations enhance photosynthesis, water uptake, and

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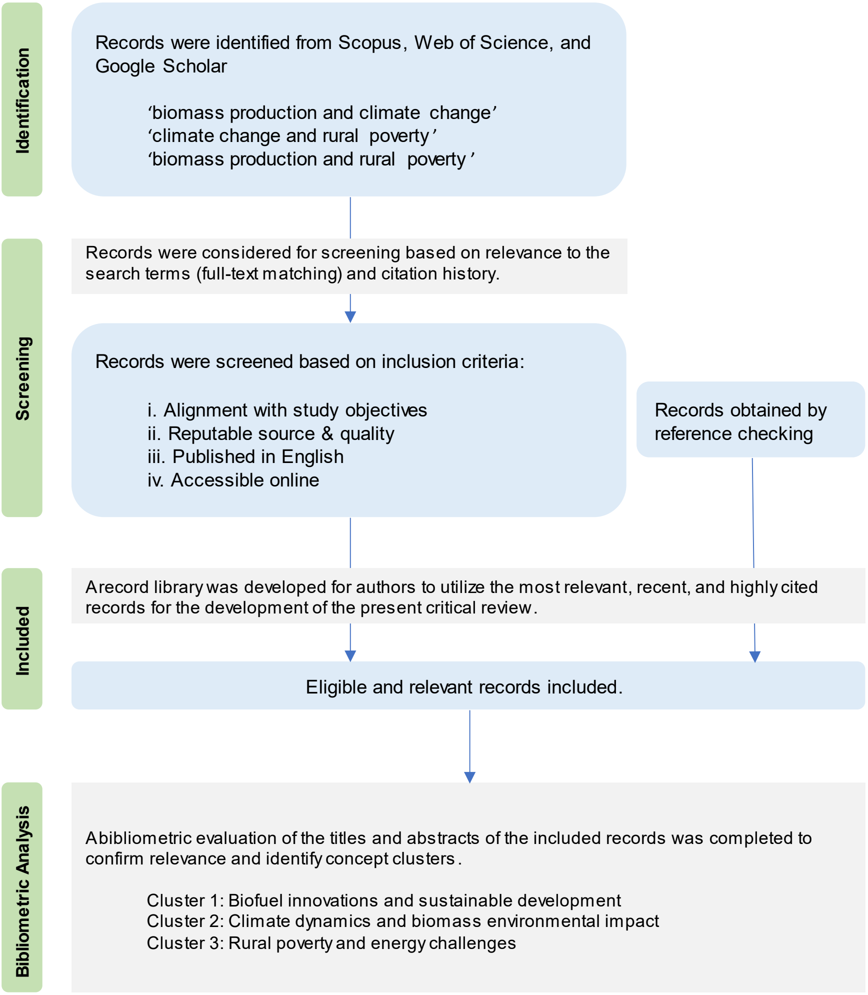
Table 1.
Review of key research examining the interplay between climate change, biomass production, and rural/remote poverty, compared to current research.

No	Factor(s)	Impact(s)	Ref.
Impact of climate change on biomass production/use			
1	Rising air temperature in the world's forests	Decrease in the above-ground biomass of old-growth forests, especially in the humid lowland areas.	Larjavaara et al. (2021)
2	Climate change alterations in temperature, rainfall patterns, drought, CO_2 levels, and air moisture	Impacts on biomass growth, productivity, chemical composition, soil microbial community, and challenges in producing fuels and value-added products from biomass	Freitas et al. (2021)
3	Changes in temperature and precipitation due to anthropogenic climate change influencing species' ranges	Inconsistent species range shifts, with many not moving towards higher latitudes, elevations, or depths as commonly expected	Rubenstein et al. (2023)
4	Previous-year precipitation regimes	Influence on current-year aboveground biomass (AGB) and plant community dynamics in a semi-arid grassland.	Gong et al. (2020)
5	Increase in annual precipitation leading to enhanced phytopathogen transmission and altered germination patterns	Promotion of tree-species coexistence in tropical regions through a rare species advantage and potential erosion of tree-species richness with decreasing precipitation	Milici et al. (2020)
6	Variability in early and late growing season temperature and precipitation	Reduction in aboveground biomass productivity in temperate grassland and potential shift in dominant functional groups	Hossain and Beierkuhnlein (2018)
7	Drought stress due to temperature dynamics, light intensity, and low rainfall	Hampering plant biomass production, quality, and energy with adverse effects on photosynthetic capacity	Seleiman et al. (2021)
8	Pre- and post-fire fuel conditions (canopy and understory fuel) using ALS data	Estimation of biomass consumption and carbon emissions from wildfires	McCarley et al. (2020)
9	Increase in temperature due to global warming	Global yield losses of rice, maize, and wheat projected to increase by 10 to 25% per degree of global mean surface warming, especially in temperate regions	Deutsch et al. (2018)
10	Water stress and elevated canopy temperature	Decreased biomass production in Panicum maximum and affected stoichiometric homeostasis, especially the C:N and C:P ratio of the plant	Viciedo et al. (2019)
11	Multifaceted effects of climate change, including high temperatures, increased concentrations of greenhouse gases (especially CO_2), soil salinity, drought, and frequent extreme weather events	Affects plant cell wall biogenesis and modification, leading to potential changes in the structural components of the cell wall. This, in turn, can influence crop productivity and the tolerance of crops to climate-related stresses	Ezquer et al. (2020)
12	Elevated atmospheric CO_2 concentration and elevated temperature	Alterations in P. maximum cell-wall structure, specifically reduced starch content and crystallinity index of cellulose, increased cellulose content, and improved cellulose surface exposure/accessibility, resulting in lower recalcitrance in biomass and improved bioenergy production potential	de Freitas et al. (2022)
Environmental impacts of biomass production/use			
13	Agroforestry systems (AFS) and practices across varied climatic conditions in India	Varied carbon sequestration and biomass across India's agro-climatic zones, influenced by specific tree species in the agroforestry system	Panwar et al. (2022)
14	Multi-cropping systems (sole, binary, and trinary crops)	Improved soil properties, including higher total nitrogen, organic carbon content, and enzyme activity in multi-cropping systems compared to sole crops, leading to better soil conservation and sustainable agro-ecosystems	Rudinskienė et al. (2022)
15	Sustainable biomass production and bioenergy cropping systems	Reduced GHG emissions, minimized environmental issues from fossil fuels, synergistic benefits for food security and bioenergy, and holistic benefits over fossil fuels when sustainably managed	Souza et al. (2017)
16	Development and production of bioenergy and its associated practices	Bioenergy production has environmental impacts, but careful management and choices can mitigate these effects, leading to sustainable development	Wu et al. (2018)
Climate change and rural/remote poverty			
17	Climate change and its impact on traditional knowledge, economic disadvantages, high food prices, lack of transportation, and food safety among Indigenous peoples in Canada	Affects all four pillars of food security (availability, access, utilization, and stability), especially in remote communities, leading to issues such as a lack of availability of traditional and market foods and a loss of traditional knowledge and skills	Shafiee et al. (2022)
18	Inequalities, including gender and social disparities, in the face of climate change	Vulnerable populations, particularly impoverished rural women and children from underdeveloped countries, are more adversely affected by the effects of climate change, with areas like food security and energy poverty under-researched	Pérez-Peña et al. (2021)
19	Physical impacts of climate change on various sectors	Negative consequences for poverty and impoverished individuals at the household level, emphasizing the importance of rapid and inclusive development in reducing these impacts	Hallegatte and Rozenberg (2017)
20	Impacts of climate change through agriculture, ecosystems, natural disasters, and health	Amplification of poverty, emphasizing the need for strategies to mitigate these impacts	Hallegatte (2016)

Table 1.
Continued.

No	Factor(s)	Impact(s)	Ref.
Biomass production/use and rural/remote poverty			
21	Massive use of biomass in Chinese rural households	Strong relationship to living standards, poverty alleviation, air pollution, and health	Wu et al. (2019)
22	Dependency on crude oil import in India and unavailability of sufficient feedstocks for bioethanol and biodiesel production	Government initiatives needed to ensure feedstock availability for the biofuel industry, promotion of advanced research, and incentivization programs for biomass-related activities leading to rural employment and consistent feedstock availability	Joshi et al. (2017)
23	Exposure to indoor air pollution due to solid biomass fuels	There is a strong association between indoor air pollution caused by biomass fuels and the risk of COPD.	Pathak et al. (2020)
24	Use of small-scale gasifiers and technological options to generate electricity in situ from biomass	Reduction of energy poverty in rural communities, improving the welfare of almost 10 million people, and promoting sustainability in societies	Lozano et al. (2023)
25	Rapid development of the biofuel industry	Worsening of food security in developing countries	Subramaniam et al. (2019)
26	Income, residents' consumption habits, and technical issues with clean energy equipment	Limitations in the energy choices of rural households in Qinghai and challenges in transitioning to a more efficient energy structure	Bai et al. (2023)
Climate change, biomass production/use, and rural/remote poverty			
27	Interrelation between climate change, biomass production disruptions, and increased rural/remote poverty	How do climate-induced changes and fluctuations in biomass production amplify the vulnerability to poverty in rural communities?	**Present Study**



Records were identified from Scopus, Web of Science, and Google Scholar

'biomass production and climate change'
'climate change and rural poverty'
'biomass production and rural poverty'

Records were considered for screening based on relevance to the search terms (full-text matching) and citation history.

Records were screened based on inclusion criteria:

i. Alignment with study objectives
ii. Reputable source & quality
iii. Published in English
iv. Accessible online

Records obtained by reference checking

A record library was developed for authors to utilize the most relevant, recent, and highly cited records for the development of the present critical review.

Eligible and relevant records included.

A bibliometric evaluation of the titles and abstracts of the included records was completed to confirm relevance and identify concept clusters.

Cluster 1: Biofuel innovations and sustainable development
Cluster 2: Climate dynamics and biomass environmental impact
Cluster 3: Rural poverty and energy challenges

Fig. 1. Flowchart illustrating the step-by-step process taken to screen and identify relevant literature.

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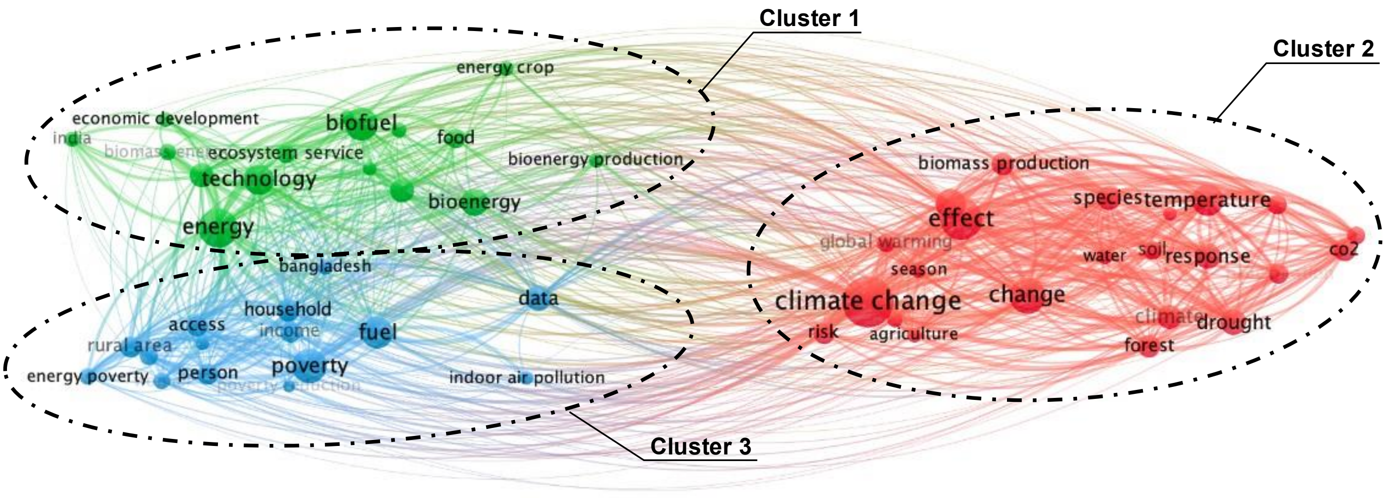

Cluster 1: Biofuel Innovations and Sustainable Development
Cluster 2: Climate Dynamics and Biomass Environmental Impact
Cluster 3: Rural Poverty and Energy Challenges

Fig. 2. Bibliographic coupling clustering, based on titles and abstracts, highlighting the key research concepts in the intersection between climate change, biomass production, and rural/remote poverty.

carbon availability while reducing dark respiration (Huang et al., 2007; Holtum and Winter, 2010; de Almeida Castanho et al., 2016). A study indicated that an elevated concentration of CO_2 (e.g., 475–600 ppm) can increase the rate of photosynthesis by an average of 40%, and elevated CO_2 decreases plant water use by 5 to 20% (Ainsworth and Rogers, 2007). Under increasing CO_2, increased photosynthesis allows most plants to grow faster. A Free-Air Carbon Dioxide Enrichment (FACE) experiment revealed that increased photosynthesis under elevated CO_2 increases aboveground production by 17% on average (Ainsworth and Long, 2005) and belowground portion of plants by more than 30% (De Graaff et al., 2006). Additionally, CO_2 provides fertilization benefits for plants (Huang et al., 2007). On the other hand, increased CO_2 levels can affect the availability of soil minerals essential for plant development and potentially reduce their uptake. Research has shown diminished enhancement of photosynthesis by elevated CO_2 under conditions of low soil nitrogen (Ainsworth and Long, 2005; Ainsworth and Rogers, 2007). Elevated atmospheric concentrations of ozone, a by-product of GHGs, including CO_2, can damage plant leaves and result in decreased plant growth and photosynthesis (Morgan et al., 2003; Feng et al., 2008).

3.1.1.3. Climate-induced precipitation variations and biomass production

Precipitation is a critical abiotic factor influencing plant productivity in terrestrial ecosystems. Both the magnitude and frequency of rainfall events play crucial roles in biomass productivity (Gong et al., 2020). In high-altitude areas, the amount and frequency of rainfall are projected to increase with climate change. If this heightened precipitation aligns with the growing season, it could significantly enhance aboveground biomass productivity (Hossain and Beierkuhnlein, 2018; Milici et al., 2020). However, the incidence of extreme rainfall events, such as flooding, is expected to rise with changing climates (Hirabayashi et al., 2008). Flooding can lead to landslides, soil erosion, and loss of habitats or ecosystems, subsequently altering aboveground biomass production.

In contrast, arid and semi-arid regions are anticipated to see a decline in rainfall. Such areas will likely become drier, and face increased drought events in terms of duration, frequency, and intensity as the climate changes (Polade et al., 2014; Haile et al., 2020). While overall precipitation might decrease in these regions, individual rainfall events could be more intense, potentially leading to unpredictable flooding (Trenberth, 2005). These climate change-driven drought and flooding events could reduce the rate of biomass production and lead to habitat loss (Vicente-Serrano et al., 2020; Friess et al., 2022). During droughts, the availability of soil water, a critical determinant of aboveground biomass productivity, diminishes (Shao et al., 2018; Gong et al., 2020; Seleiman et al., 2021). Moreover, drought escalates the frequency and severity of wildfires, reducing the forest's biomass provision potential and the ability of impacted ecosystems to supply biomass for energy (Duff et al., 2019; McCarley et al., 2020).

3.1.1.4. Climate-induced emergence and reemergence of pests and diseases impacting biomass production

Environmental factors such as temperature and moisture play a significant role in plant pathogen development and transmission. There is an ideal temperature and moisture range for disease development in every plant-pathogen relationship. Typically, warm temperatures combined with high air humidity and soil moisture foster most plant diseases. Deviations from these ideal conditions lead to significant reductions in disease incidence (Sturrock et al., 2011; Ramsfield et al., 2016). Furthermore, warming climates may accelerate pest population growth; however, insect populations in tropical regions might diminish as temperatures could become excessively high (Deutsch et al., 2018). Climate change profoundly affects the epidemiology of infectious diseases by altering the geographic distributions of microbes and vectors. Global warming will result in more hospitable environments for pests in northern climates, causing a northward migration of pests and diseases (Parmesan, 2006; Dukes et al., 2009). Insects not only facilitate pathogen entry by wounding plants but also serve as vectors or carriers of these pathogens (Agrios, 2008; Wielkopolan et al., 2021). Moreover, insects themselves can destroy plants in addition to their vector roles. For example, mountain pine beetle infestations have killed over 1 million ha of western yellow pine and 1.5 million ha of pion pine on the Colorado Plateau and the central Rocky Mountains, and over 37 million ha of forest in British Columbia are likely to be affected between 2000 and 2020 (Kurz et al., 2008). Beyond temperature, alterations in precipitation patterns across seasons can also trigger tree diseases (Jamieson et al., 2012). While increased rainfall promotes pathogen transmission, reduced rainfall or prolonged drought can make plants more susceptible to diseases (Milici et al., 2020). For instance, between 2010 and 2021, an estimated 170 million trees died in forest regions of California, where most of these trees were stressed because of drought or higher temperatures and decreased water availability, leaving them more susceptible to insects and infections (U.S. Department of Agriculture Forest Service, 2020a and b). However, climate change, in combination with prolonged drought periods, might actually reduce both the frequency and severity of diseases (Allen et al., 2010).

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3.1.1.5. Climate-induced soil quality variations and biomass production

Climate conditions, particularly increases in temperature and atmospheric CO_2 levels, significantly influence soil quality, which subsequently impacts biomass productivity (Rosenzweig and Hillel, 2000; Mondal, 2021). Climate change modifies both the physical and chemical properties of soils, potentially leading to land degradation (Rosenzweig and Hillel, 2000; Mondal, 2021). Elevated temperatures can elevate the soil's salt content, reduce its porosity, enhance compactness, accelerate erosion, decrease water retention capacity, and diminish the organic carbon content (Mondal, 2021). Intense and heavy rainfall can damage soil aggregates, heighten the risk of erosion, induce soil acidification, lead to the loss of essential soil nutrients (notably nitrogen), create hypoxic conditions in poorly drained soils, and increase toxicities of certain minerals, such as Fe, Mn, Al, among others (Mondal, 2021). On the other hand, reduced rainfall can elevate soil salt content, hinder the diffusion and mass flow of water-soluble nutrients, result in soil moisture deficits, cause nutrient loss from the root zone, and decrease the nutrient acquisition capacity of the root system (Mondal, 2021). Furthermore, a rise in atmospheric CO_2 can affect soil carbon availability, microbial activity, and fungal populations within the soil (Pritchard, 2011; Mondal, 2021).

3.1.2. Effects of climate change on the production and utilization of biomass energy

Beyond its direct influence on biomass resources and yields, climate change also affects biomass energy production and utilization processes. Environmental and climate conditions play pivotal roles in shaping the biomass energy production processes and how this energy is used (Schaeffer et al., 2012). The implications of these climate conditions on energy production and utilization are discussed below.

3.1.2.1. Climate-induced variations in nutrient inputs and chemical compositions of biomass feedstocks

Climate conditions not only affect the quantity but also the quality of biomass feedstocks. Key parameters critical for efficient biomass production, such as chemical composition, calorific value, potential ethanol yields, and nutrient inputs, are influenced by environmental and climate factors (Gent et al., 2017; Freitas et al., 2021). For example, the organic matter composition and the lignocellulosic composition of biomass resources for bioenergy use are subject to changes based on varying climate and environmental factors (Viciedo et al., 2019). The biosynthesis of plant cell walls, which serve as the primary carbon sinks, is controlled by photosynthesis and is subject to dynamic regulation by environmental factors (Ezquer et al., 2020). Climate variables, such as temperature and CO_2 levels, can influence cellulose synthesis (Teng et al., 2006). Additionally, the xylose-to-arabinose ratio, a critical factor in determining biomass recalcitrance, can be altered due to heat stress (de Freitas et al., 2022).

3.1.2.2. Vulnerability of conventional power systems to climate change and the rising demand for energy services

There are myriad environmental and climatic implications for the energy sector. For instance, droughts can limit water resources essential for hydropower. Shifts in cloud cover, temperature, and atmospheric pressure can impact the efficiency of wind and solar energy sources (Schaeffer et al., 2012; Jasiūnas et al., 2021). Severe weather events, such as hurricanes, may cause energy infrastructure interruption. Extreme weather occurrences may also affect overall energy demand. The global energy demand has risen dramatically and is expected to rise even further as the effects of climate change intensify. This increase in demand for energy services will exert pressure on the existing infrastructure. As a result, people may be forced to utilize biomass energy sourced from firewood, agricultural wastes or residues, or wild plant matter (Chang et al., 2007).

3.1.3. Environmental consequences of biomass energy production

Biomass energy production plays a multifaceted role in environmental management. The possible environmental benefits and consequences associated with biomass energy production are detailed below (Abbasi and Abbasi, 2010; Herbert and Krishnan, 2016).

3.1.3.1. Positive impacts of biomass energy production on the environment

While there are potential adverse impacts, it is important to recognize the significant positive contributions biomass energy can make towards environmental sustainability. First, biomass, particularly when derived from agroforestry, contributes to capturing atmospheric CO_2, mitigating the impact of GHGs. The carbon sequestration potential of biomass is crucial in combating climate change (Jose and Bardhan, 2012; Panwar et al., 2022). When managed sustainably, bioenergy crops can serve as a carbon sink, potentially offsetting emissions from fossil fuels (Lemus and Lal, 2005). Second, utilizing organic waste for bioenergy production aids in managing and reducing waste, thereby contributing to lower environmental pollution. This can significantly mitigate the impact of wastes in landfills, reducing methane emissions and potential soil and water contamination (Machado-Filho, 2008). Producing bioenergy from waste can also reduce deforestation, which further helps in climate regulation (Katuwal and Bohara, 2009). Third, biomass cultivation can enhance soil health and biodiversity, especially when integrated into existing agricultural systems (like crop rotation or multi-cropping systems) (Rudinskienė et al., 2022). Such practices can improve land use efficiency, foster ecological balance, and reduce the need for chemical fertilizers, further aiding in GHG reductions (Tilman et al., 2006; Lal, 2008; Boincean and Dent, 2019). Finally, biomass energy offers a renewable source of power and heat, contributing to the diversification of energy sources and reducing reliance on fossil fuels. This transition to renewable energy sources is essential for sustainable development and reducing overall environmental impact (Souza et al., 2017). In addition, bioenergy can utilize various wastes and residues, thus reducing environmental issues caused by excess waste and combating energy poverty.

3.1.3.2. Addressing potential negative impacts of biomass energy production on the environment

Despite its advantages as a renewable, low-sulfur fuel, using biomass as an energy source is not free from potential adverse environmental impacts. First, if biofuels are not managed sustainably, they can pose threats to ecosystems and biodiversity. The increasing demand for biofuel production can lead to altered ecosystems and decreased biodiversity (Koh, 2007). For example, the uncontrolled use of feedstocks for biomass production creates a substantial threat to tropical ecosystems through deforestation and conversion of protected lands for biofuel crop production (Hansen et al., 2008). In temperate regions, there is growing concern about converting grasslands and conserved areas for biofuel crops (Tilman et al., 2006; Meyerson, 2008). Studies have shown that replacing natural habitats with biofuel feedstock plantations generally houses significantly fewer biodiversity species than intact ecosystems (Koh and Wilcove, 2007).

Second, although biomass energy production is considered a cleaner alternative for reducing emissions of GHGs, it does emit gases such as CO_2, nitrous oxide, and methane, along with other pollutants like polycyclic organic matter, particulate matter, carbon monoxide, hydrogen sulfide, hydrocarbons, ammonia, hydrogen cyanide, carbonyl sulfide, and carbon disulfide (Abbasi and Abbasi, 2010; Li et al., 2021). These pollutants are generated during various processes of biomass energy production. For instance, in traditional biomass energy use, incomplete combustion of wood materials can release these gases (Herbert and Krishnan, 2016). Furthermore, processes like biochemical, thermochemical, gasification, and pyrolysis used in biomass conversion to fuels are sources of the aforementioned GHGs, unconverted hydrocarbons, and other trace gases (Abbasi and Abbasi, 2010).

Third, bioenergy processes contribute to generating wastewater and solid waste (Abbasi and Abbasi, 2010). One main issue is the potential competition for arable lands, which are crucial for food and fiber production. The production of biomass feedstock can result in soil disturbances, nutrient losses, and deteriorated water quality. During the biochemical conversion of biomass to fuel, pollutants are emitted into the air, while solid wastes and wastewater are also produced. In contrast, thermochemical conversion discharges particulates, carbon monoxide, hydrogen sulfide, and polycyclic organic matter. Managing the resulting wastewater and solid waste poses additional environmental challenges (Abbasi and Abbasi, 2010).

Finally, using agricultural residues as biomass feedstocks can lead to land and water degradation. When agricultural residues remain in place, they play a role in preventing erosion, conserving nutrients and water, and sustaining soil organic content. Diverting these residues from agricultural lands for energy purposes can disrupt land stability and fertility by increasing erosion and subsequent depletion of topsoil, essential nutrients, and organic matter. This soil erosion can significantly degrade water quality as nutrient pollution and sedimentation increase due to surface runoff and infiltration (Herbert and Krishnan, 2016; Wu et al., 2018). Furthermore, bioenergy production can exacerbate water scarcity, especially considering the water needs of certain bioenergy crops (Gasparatos et al., 2011; Hoekman et al., 2018). For instance, some bioenergy crops, like corn, have been shown to demand more water than other crops, such as wheat and soybean (Wu et al., 2018).

3.2. Climate change and rural/remote poverty

The concept of poverty extends beyond monetary considerations and has been considered as a multidimensional condition that is impacted by individual characteristics, such as income and capabilities, as well as broader factors like community characteristics, social norms, the economic environment, political atmosphere, and governance (Leichenko and Silva, 2014). Simply put, poverty is defined as not having sufficient resources to meet one's needs, though the interpretation of 'needs' and 'resources' can vary considerably based on geographic location (Leichenko and Silva, 2014). Data from the last decade estimates approximately 79% of the world's impoverished population reside in rural and remote areas, with the poverty rate in these areas being over three times higher than that of urban centers (Olinto et al., 2013; United Nations Statistics Division, 2023). It is also estimated that about 63% of the global impoverished population is employed in the agriculture sector, primarily in smallholder farming (Olinto et al., 2013). The agriculture sector is highly dependent on climate factors, making it one of the human activities most vulnerable to climate change (Hertel et al., 2010).

There is a close relationship between poverty, especially in rural/remote areas, and vulnerability to climate change; however, it should be noted that merely being 'poor' does not inherently make an individual, household, or community more susceptible to the impacts of climate change. Instead, it is a myriad of interconnected factors that increase vulnerability and can potentially exacerbate poverty (Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017; Pérez-Peña et al., 2021). For the purposes of this section, we will discuss the factors that play a direct and indirect role in the multi-faceted relationship between climate change and rural/remote poverty.

3.2.1. Direct Links between climate change and rural/remote poverty

The main direct link between climate change and rural/remote poverty is via agriculture, both in terms of production and livelihoods and the resulting impact of the cost of food. Climate adversities, as a result of climate change, such as increasing average temperatures (Hallegatte and Rozenberg, 2017), shifting precipitation patterns, extreme weather events, and greater climatic variability can substantially impact agricultural production (Leichenko and Silva, 2014; Hallegatte, 2016; Pérez-Peña et al., 2021). Further, ecosystem services, particularly biodiversity along with soil and water regulation, are impacted by climate change (Fisher et al., 2013; Howe et al., 2013), which in turn affects agricultural crops, livestock grazing, fishing, and hunting (Fisher et al., 2013; Howe et al., 2013; Hallegatte, 2016). Beyond navigating the direct impact of climate change on sustaining agricultural crops, climate variability and the fear of the unknown lead farmers to be more risk-averse. For example, selecting crops that are less affected by rainfall fluctuations often leads to less profitable investments (Brown et al., 2011; Leichenko and Silva, 2014). The rural/remote impoverished population typically lacks diverse livelihood options and tends to rely more on climate-sensitive agricultural sectors such as smallholder farming, forestry, fishing, or pastoralism (Leichenko and Silva, 2014). This vulnerability is further accentuated among Indigenous peoples living in rural and remote areas, for whom climate change has impacted all pillars of food security, ranging from availability, access, and utilization to stability (Shafiee et al., 2022). These communities, deeply rooted in traditional agricultural practices, are often the first to face the brunt of climatic adversities.

Rural agricultural producers' experiences with poverty and food security vary based on their exposure to climatic challenges. For instance, rural/remote producers impacted by climate-related shocks may experience reduced food production and reduced income, leading to higher degrees of poverty and food insecurity, whereas those not impacted by climate-related shocks may be able to yield a greater profit due to increasing food costs (Hertel et al., 2010; Leichenko and Silva, 2014; Hallegatte, 2016). In a global setting, declines in agricultural production will lead to a substantial increase in the price of foods, specifically crops that are highly dependent on rainfall or temperature conditions, such as maize and other coarse grains (Hertel et al., 2010). However, Hertel et al. (2010) consider production yields or commodity price changes a poor predictor of climate change's impact on poverty. They argue that the consistent impact of climate change on the cost of living at the poverty line is more indicative, emphasizing the role of price-induced earning changes and their impact on household income (Hertel et al., 2010).

3.2.2. Indirect links between climate change and rural/remote poverty

The multifactorial relationship between climate change and rural/remote poverty has many indirect links, including impacts on the local economy, health inequities, and social-cultural factors. Firstly, climate change is observed to slow economic growth and development in rural/remote areas (Brown et al., 2011), which is likely to impact poverty rates directly as well as poverty alleviation efforts (Thurlow et al., 2012; Leichenko and Silva, 2014; Hallegatte, 2016). For example, a modeling study investigating household poverty in Zambia showed that climate variability decreased economic growth by 4% over a ten-year period, increasing the number of people below the poverty line by an additional 2% (Thurlow et al., 2012). Interestingly, a longitudinal analysis of over 125 countries from 1950 to 2005 found that an increase in mean temperatures reduces economic growth by 1.3% in low-income countries (Dell et al., 2012). Furthermore, climate change and the resources to mitigate climate-related shocks substantially affect poverty alleviation efforts either by making asset accumulation more difficult for rural/remote communities, heightening the risks associated with 'cash crops', reducing tourism and tourism-based developments (Leichenko and Silva, 2014), or diverting funds from economic development efforts to climate adaption strategies (Leichenko and Silva, 2014; Hallegatte, 2016; Hallegatte and Rozenberg, 2017).

Secondly, impoverished populations are disproportionality affected by negative physical health conditions. Certain illnesses, such as vector-borne and water-borne diseases like malaria, dysentery, and cholera, are expected to increase as a result of climate change, consequently contributing to reduced productivity and income loss, exacerbating the effects of poverty (Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017). Lastly, the rural/remote poor are more likely to have fewer assets to help them recover in the event of climate shocks, and they are more likely to be less resilient to climate shocks; for example, they might lack appropriate insurance coverage for adverse climatic events (Leichenko and Silva, 2014) or rural shelters in developing countries might be more susceptible to extreme weather events than modern housing in urban centers (Hallegatte, 2016).

The relationship between climate change and rural/remote poverty is multi-faceted and highly dependent on the socio-cultural, environmental, and political landscape, influencing the impoverished rural/remote population's vulnerability to climate change. The future implications of climate change on rural/remote poverty are challenging to estimate due to the unknown nature of climate variability as well as the population's ability to cope.

3.3. Biomass production and rural/remote poverty

Rural and remote centers, primarily in developing countries, have an inherent dependency on biomass for various purposes. Biomass, primarily consisting of wood, crop residues, and animal dung, serves as a significant source of energy for cooking, heating, and sometimes even lighting and influences various facets of rural/remote life, from economic to social dimensions. The interplay between biomass production and rural/remote poverty offers both opportunities and challenges in the face of growing populations and changing climatic conditions.

3.3.1. Dependence on biomass production and use in rural/remote centers – economic, livelihood, and sustainability implications

Biomass, as a source of renewable energy, holds significant potential for transforming rural and remote communities, especially in developing nations. Its capacity to serve as a primary fuel for household needs and as a catalyst for economic growth is counterbalanced by challenges related to sustainability, health implications, and food security. This section explores the economic, livelihood, and sustainability implications of biomass production in rural and remote areas.

3.3.1.1. Biomass in rural/remote development: economic opportunities and challenges for poverty alleviation

Biomass, as a renewable energy source, plays a pivotal role in the global energy matrix. In numerous developing regions, biomass is a primary energy source used for domestic purposes such as cooking, lighting, heating, and operating household appliances (Smith and Sagar, 2014; Wu et al., 2019). Notably, cooking energy demands account for approximately 80% of household energy needs in rural settings (Kaygusuz, 2011). Modern technologies are gradually paving the way to transform these resources into advanced bioenergy forms like biodiesel, bioethanol, biogas, and biomass-generated electricity, among others (Guta, 2012; Maltsoglou et al., 2013). The dependency on biomass brings with it a range of economic implications – some beneficial and others potentially adverse. From an economic perspective, biomass production can be beneficial, particularly for rural and developing areas (Gerber, 2008; Kaygusuz, 2011; Faße et al., 2014). Key among these benefits is the potential to create new markets, provide consistently priced heating sources, and prevent regional economic outflows, subsequently contributing to poverty reduction (Ewing and Msangi, 2009; Grebner et al., 2009; Bailey et al., 2011). For instance, in Malawi, the bioenergy supply chain employs approximately 2% of the entire workforce (Openshaw, 2010). Turning our attention to Tanzania, agroforestry significantly influences certain village economies, with households deriving an average of 11.9% of their agricultural income from it (Faße et al., 2014). Another study focused on the potential of biomass district heating (BDH) to invigorate the rural economy of New York State's Tug Hill region demonstrated that an annual expenditure of 11.4 million USD across a 20-year span for construction, biomass procurement, and heat production through BDH would spur 18.7 million USD in local economic activities and create 143 jobs within the three-county model region (Hendricks et al., 2016a).

Localized, small-scale bioenergy development holds special promise for impoverished rural communities (Gerber, 2008; Chakrabarty et al., 2013). Computable general equilibrium models from Ethiopia (Levin et al., 2012) and Tanzania (Arndt et al., 2012) indicate bioenergy's potential in reducing poverty. Biomass remains a dominant form of renewable energy, with its demand expected to surge (International Energy Agency, 2017). For context, biomass-based sources like wood and biofuel crops contribute approximately 60% of the European Union's renewable energy output (Nicolae et al., 2019). The growing prominence of the biomass sector, particularly in biofuel production, unveils myriad opportunities for developing nations. Governments envision bioenergy as a strategy to decrease reliance on imported fuels and invigorate economic growth by spawning new employment avenues, subsequently enhancing household earnings (Openshaw, 2010). This perspective aligns with the projection that biofuel crops could introduce novel income streams for rural agriculturists, although the economic advantages can vary regionally (Domac et al., 2005; Arndt et al., 2011b). A study by Hendricks et al. offered valuable insights into the viability of biomass for heating. Employing an innovative assessment tool, their research ascertained that BDH could potentially offer prices more competitive than #2 fuel oil in eight of the ten rural villages studied, leading to an annual cost-saving of nearly 500,000 USD. It is worth noting that the majority of these expenses (over 80%) were capital-related. A modest 1% reduction in capital costs could result in yearly savings of 93,000 USD. Even with potential future price reductions in #2 fuel oil, its unpredictable pricing ensures that these villages still have a 22-53% chance of BDH being a viable option over a 20-year period (Hendricks et al., 2016b).

On the other hand, biomass, while economically advantageous in terms of fuel costs, presents several economic challenges. A primary economic barrier associated with biomass lies in the elevated capital costs of boilers essential for its conversion (Maker, 2004; Becker et al., 2014). The inherent attributes of biomass, including its lower energy and mass density compared to fossil fuels, introduce logistical and economic complications. The biomass conversion efficiency for heating and cooking ranges from 10% to 20%, contributing to indoor pollution (Antar et al., 2021). Direct combustion plants, where biomass is incinerated to produce steam that powers a turbine generator, typically have an efficiency between 15% and 35% (Malico et al., 2019). Consequences include seasonal availability (Miao et al., 2012), increased transportation expenses due to its bulkiness (Miao et al., 2012; Joshi et al., 2017), and the demand for extensive storage infrastructure (Vallios et al., 2009; Miao et al., 2012). Such intrinsic difficulties often deter the broad adoption of biomass heating solutions, especially in contexts of individual households or smaller businesses (McKendry, 2002).

3.3.1.2. Health impacts of biomass usage in rural/remote settings

In recent years, the sustainable production and use of biomass have faced challenges, raising concerns about health impacts and environmental ramifications (Diaz-Chavez et al., 2015). The prevalent use of stoves demanding substantial biomass quantities contributes to dwindling biomass resources. Such inefficient appliances produce copious amounts of smoke, degrading indoor air quality and disproportionately affecting women and children (Po et al., 2011; Pathak et al., 2020). To illustrate, indoor smoke from traditional fuels is linked to an estimated 2.5-4.0 million annual fatalities (Lim and Seow, 2012). A meta-analysis of 25 studies has highlighted the association between domestic solid biomass fuel usage and a myriad of respiratory ailments in rural populations (Po et al., 2011). Likewise, in another meta-analysis, solid biomass fuels were found to increase the risks of chronic obstructive pulmonary disease (COPD) and chronic bronchitis, with geographical variations in risk (Pathak et al., 2020). The health repercussions for women using traditional biomass for cooking are notably adverse, with a significant percentage of chronic obstructive pulmonary disease-related deaths among women attributed to indoor air pollution (Smith et al., 2004; Rehfuess et al., 2006). Exposure levels are particularly elevated among women and children, who tend to spend more time indoors during cooking activities (Khalequzzaman et al., 2010). Innovative technologies like biogas systems present solutions that mitigate both the high biomass consumption issue and health detriments (Diaz-Chavez et al., 2015). A recent study in Mexico highlighted that harnessing residual biomass for electricity through gasifiers holds the potential to uplift nearly 10 million individuals in rural communities (Lozano et al., 2023).

3.3.1.3. Balancing biomass production, food security, and sustainability amidst rising demands

The ascent of bioenergy is not without its caveats. A significant debate focuses on the feasibility and ethics of introducing bioenergy production in developing nations (Karp and Halford, 2011). Even as its proponents sing praises, concerns about societal fairness and ecological sustainability persist. Of paramount concern is the potential impact on food security in areas already confronting food shortages. This underscores the imperative to closely scrutinize the interplay between bioenergy and food crops (Fischer et al., 2009; Maltsoglou et al., 2013). Many energy crops, such as sugar cane and maize, also double as food staples. It is posited that the rising demand for biomass as bioenergy feedstocks might elevate food and feedstock prices owing to augmented demand against a shrinking supply (Fischer et al., 2009; Negash and Swinnen, 2013; Subramaniam et al., 2019). The bioenergy boom could also prompt the transformation of non-farming lands into agricultural territories (Whitaker et al., 2018). This momentum has introduced unintended outcomes, notably heightened food scarcity, rising poverty, and the displacement of small-scale farmers and indigenous communities from their territories (Kaygusuz, 2011). Compounding these issues are concerns related to neocolonial practices. Economic incentives might propel a shift from food to bioenergy crop production unless stringent policies are instituted to counteract this transition.

In several developing and underdeveloped areas, biomass remains a primary energy source for heating and cooking. Regrettably, its procurement is frequently unsustainable, resulting in widespread forest degradation. Some regions have witnessed biomass resources exploited beyond sustainable levels, leading to shortages and ecological degradation (Sovacool, 2012; GLOBAL-BIO-PACT, 2013). The biomass conversion efficiency for these applications is notably low, typically oscillating between 10% and 20% (Antar et al., 2021). This unchecked and growing utilization, fueled by burgeoning populations, leads to sharp declines in biomass in numerous rural locales. Overharvesting culminates in severe environmental repercussions: deforestation, soil erosion, and biodiversity diminution, all of which subsequently impair agricultural output, exacerbate food scarcity, and amplify food insecurity (Mbow et al., 2014). The escalating global populace amplifies the dilemma of fulfilling concurrent food and energy requisites constrained by the planet's finite resources (Haberl et al., 2013). Biomass use must not just be efficient but also effective, channeling it toward its highest value based on context (Garnett et al., 2015; Muscat et al., 2020).

3.3.2. Sociocultural implications of biomass dependence

Biomass dependence, especially in rural/remote communities, carries profound sociocultural implications. From traditional cooking methods to the labor-intensive collection process, the role of biomass as an energy source is intertwined with societal norms, economic factors, and deeply ingrained gender roles.

3.3.2.1. Impact of household welfare on biomass dependence

It is pivotal to recognize the nuanced relationship between biomass scarcity and household welfare. Analyses have indicated that biomass scarcity can result in marginally lower household welfare, particularly affecting the rural/remote poor. For instance, in Malawi, it has been determined that 80% of rural poor households could significantly benefit from an increase in community biomass (Bandyopadhyay et al., 2011). However, in the face of such scarcity, the minor decrease in welfare suggests the resilience and adaptability of households. They have developed various coping mechanisms to deal with this scarcity, emphasizing the need to understand these strategies when considering deforestation and degradation reduction initiatives (Bandyopadhyay et al., 2011). Moreover, the structure of energy consumption in these communities is driven by the high reliance on biomass energy, primarily because it can be sourced from the local environment without direct monetary costs. The associated opportunity costs for collecting biomass are perceived to be low, especially since the primary collectors are often women and children, segments of the population that face higher unemployment rates or undervaluation of their labor, a predicament often amplified among the rural/remote poor (Bai et al., 2023). Furthermore, household size and structure, which are often larger among the rural/remote poor, influence fuel choices. Such households diversify their fuel sources rather than completely switching away from biomass (Heltberg, 2004). This could be due to the availability of more hands to assist in a collection or a combination of diverse preferences within the household.

3.3.2.2. Gender roles in biomass production and dependence

In many developing regions, especially the impoverished rural and remote areas, the collection of biomass, particularly wood fuel, is vital for energy requirements. Intriguingly, this task largely falls upon women and children, making it a gendered responsibility deeply linked to the dynamics of rural poverty (Huda et al., 2014). This tradition originates from longstanding practices in which rural women, often those living in conditions of poverty, are tasked with procuring essentials for the household, from water and food to energy (Rehfuess et al., 2006; Oparaocha and Dutta, 2011). These gender roles often become obstacles in the path of gender equality. As resources like wood become scarcer due to reasons like overexploitation and the impacts of climate change, these entrenched gender roles might further solidify, making the shift toward gender equality even more challenging (Habtezion, 2016).

3.3.2.3. Health implications in biomass production and use

The physical aspect of biomass collection, especially for women, cannot be understated. Women carrying heavy loads over vast distances often face health complications, which in impoverished conditions can lead to various health complications (Kaygusuz, 2011). Over time, these complications can result in chronic health conditions. Coupled with this is the exposure to potential dangers. The further depletion of local biomass sources compels women to venture farther from their homes, heightening their risk of wildlife encounters and personal assaults, a situation worsened by the vulnerabilities of rural poverty (Huda et al., 2014). Beyond the physical toll, there are also significant health hazards posed by using solid fuels, which are prevalent among the rural poor. As mentioned earlier, women and children, primarily from impoverished backgrounds, are exposed to harmful indoor smoke, with dire health implications in the long run (Habtezion, 2016).

3.3.2.4. Socio-economic considerations and the implications of education on biomass dependence

The reliance on biomass for energy in impoverished rural areas has marked socio-economic implications that are directly linked to household education levels. Rural/remote poor households often have lower educational levels, which is directly related to increased dependence on biomass, which may be attributed to the limited opportunities and economic engagements available to these households, making the perceived costs of biomass collection lower than they might be for a more educated household (Barnes et al., 2010; Peng et al., 2010). Women, many from economically challenged backgrounds, spend a significant portion of their day collecting wood, leading them to forgo opportunities such as education, accessing health services, or income-generating activities (Barnes and Toman, 2006). Given women's central role in family and community well-being, this missed potential has wider repercussions on societal development. For children in these poverty-stricken rural areas, particularly girls, their involvement in biomass collection often results in reduced time dedicated to education. This not only hampers their immediate academic achievements but can have long-term effects on their career and life opportunities (Chakrabarty et al., 2013).

Furthermore, the significant time invested in biomass collection in biomass-dependent societies can translate to economic stagnation. This time could otherwise be invested in more lucrative developmental activities, fostering growth and prosperity (Pachauri and Spreng, 2004; Barnes and Toman, 2006; Ewing and Msangi, 2009). However, transitioning to modern bioenergy solutions could give communities and women tasked with biomass collection better opportunities. By adopting improved cooking stoves, for instance, there is not only a direct health benefit by reducing indoor smoke exposure but also a potential to divert labor from wood collection to more economically productive tasks (Kanagawa and Nakata, 2007). Yet, such transitions come with their challenges. While the bioenergy sector could present job opportunities for women, there is the danger of intensifying the conflict between energy and food production, especially if female labor shifts from food to biofuel production (Arndt et al., 2011a).

3.3.2.5. Cultural preferences and decision dynamics in biomass production and use

Traditional beliefs and practices, particularly among the impoverished, play an influential role in how households perceive and choose their energy sources. Despite the availability of modern fuels, many might opt for biomass due to entrenched cultural beliefs related to cooking practices or taste preferences (Masera et al., 2000; Preeti et al., 2003). This deep-seated cultural inertia can sometimes be a barrier to adopting more sustainable and health-friendly energy options. When assessing decision-making dynamics within households, gender again plays a pivotal role (Hou et al., 2018; Bai et al., 2023). Households headed by women might have a different energy consumption pattern compared to those led by men, rooted in both socio-economic circumstances and traditional norms (Hou et al., 2018; Bai et al., 2023).

3.4. Interrelation – climate change, biomass production, and rural/remote poverty

The intricate web of relationships between climate change, biomass production, and rural poverty is characterized by a series of chain reactions that have implications for the sustainability of our environment and the livelihoods of countless individuals in rural settings. Understanding these

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feedback loops offers a comprehensive view of the challenges and potential solutions inherent in these dynamics.

3.4.1. The chain reactions between vulnerability to rural/remote poverty in light of climate change and its impact on biomass production

The interplay of climate change, biomass production, and rural poverty is illustrated in **Figure 3**. Rural centers, particularly in developing countries, rely heavily on biomass for a range of functions, from cooking to heating (Maes and Verbist, 2012). When we consider the dynamic of rural poverty, this dependence is intensified by the affordability and accessibility of biomass, making it a primary energy source for many. However, this reliance is precarious. Climate change can lead to shifts in precipitation patterns, increased incidence of extreme weather events, and changing temperature regimes, all of which can negatively affect the growth and availability of biomass resources (Hirabayashi et al., 2008; Polade et al., 2014; Haile et al., 2020). Reduced biomass availability exacerbates rural poverty as it raises the opportunity cost for its collection, especially when these tasks fall to women and children (Bai et al., 2023).

Moreover, reduced biomass availability due to unsustainable harvesting practices or climate-induced changes can further deprive these communities of their primary energy source, forcing them into more unsustainable practices or the usage of costly fossil fuels if they can afford them (Hendricks et al., 2016b). The combination of climate change and over-harvesting has resulted in severe environmental repercussions such as deforestation, soil erosion, and diminished biodiversity, all of which undermine agricultural output and food security. The resultant food insecurity from the scarcity of biomass resources can intensify rural poverty even further and lead to a reinforcing feedback loop (**Fig. 4**). This downward spiral sees rural communities having less and less capacity to adapt to the changing climate.

The challenge of climate change and its impact on biomass production presents opportunities for innovation and sustainable development. However, there is the conundrum of the food-fuel nexus, where the increased demand for bioenergy might lead to heightened food scarcity, further elevating rural poverty levels (Kaygusuz, 2011). Beyond these climatic factors, the relationship between biomass energy and poverty is multifaceted. Well-designed bioenergy systems can counteract climate change (Kaygusuz, 2011; Faße et al., 2014), provide energy access, and mitigate rural poverty (Openshaw, 2010; Kaygusuz, 2011; Faße et al., 2014). With proper land management, bioenergy can enhance agricultural yields, improve food security, and reduce the need for land clearing (Sharma et al., 2016). However, poverty might deter bioenergy production since it is land-intensive, and people in impoverished circumstances might prioritize land use for immediate sustenance over long-term biomass solutions (Barnes and Floor, 1999).

Ideally, biomass application should first cater to food needs, thereafter curtailing waste before venturing into feed and fuel domains (Muscat et al., 2020). While some domains prioritize biomass for food, others advocate its conversion to bioenergy. This dichotomy further accentuates evolving societal values and contexts, like the emergent call for a circular

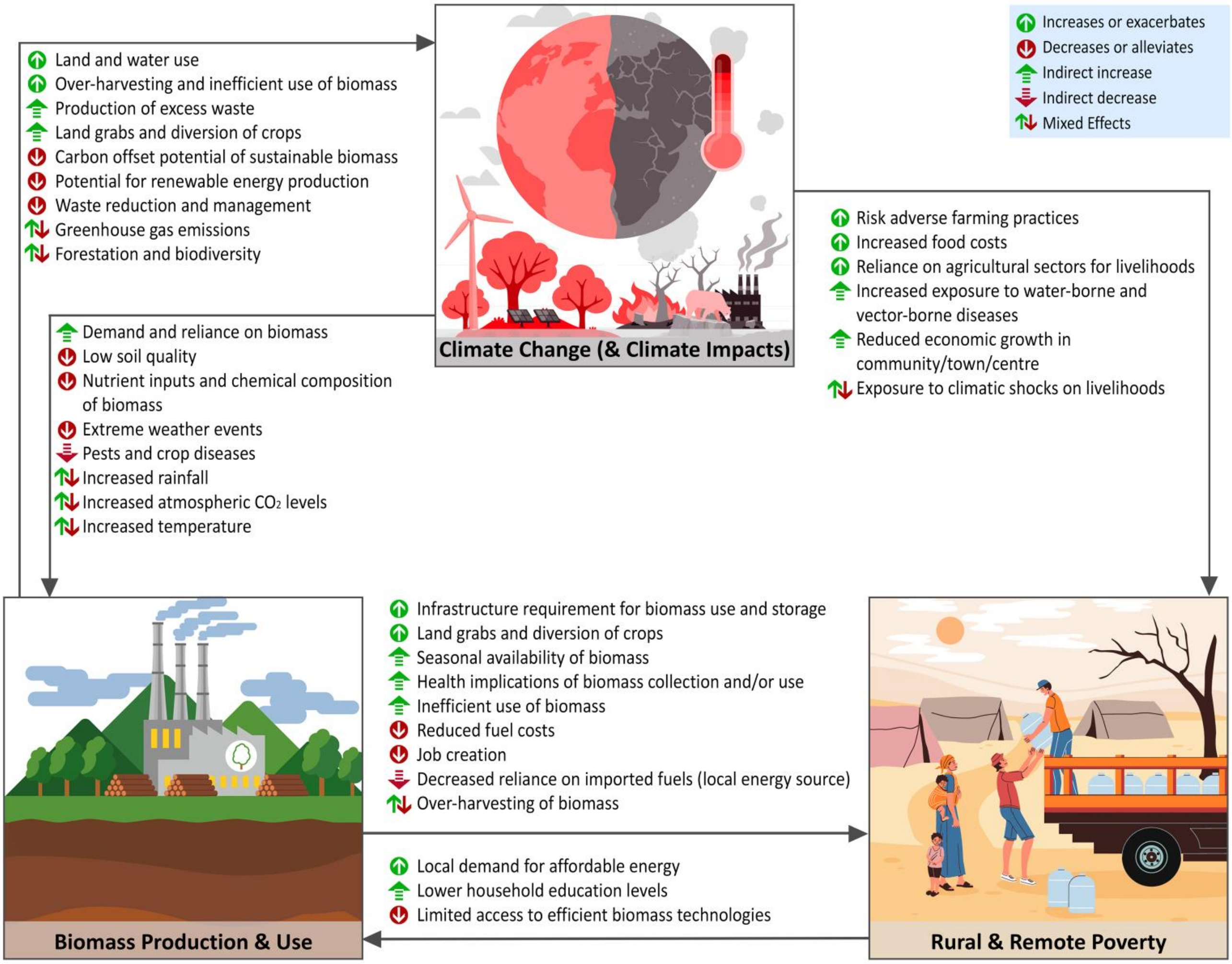

Fig. 3. Interrelation of climate change, biomass production, and rural/remote poverty.

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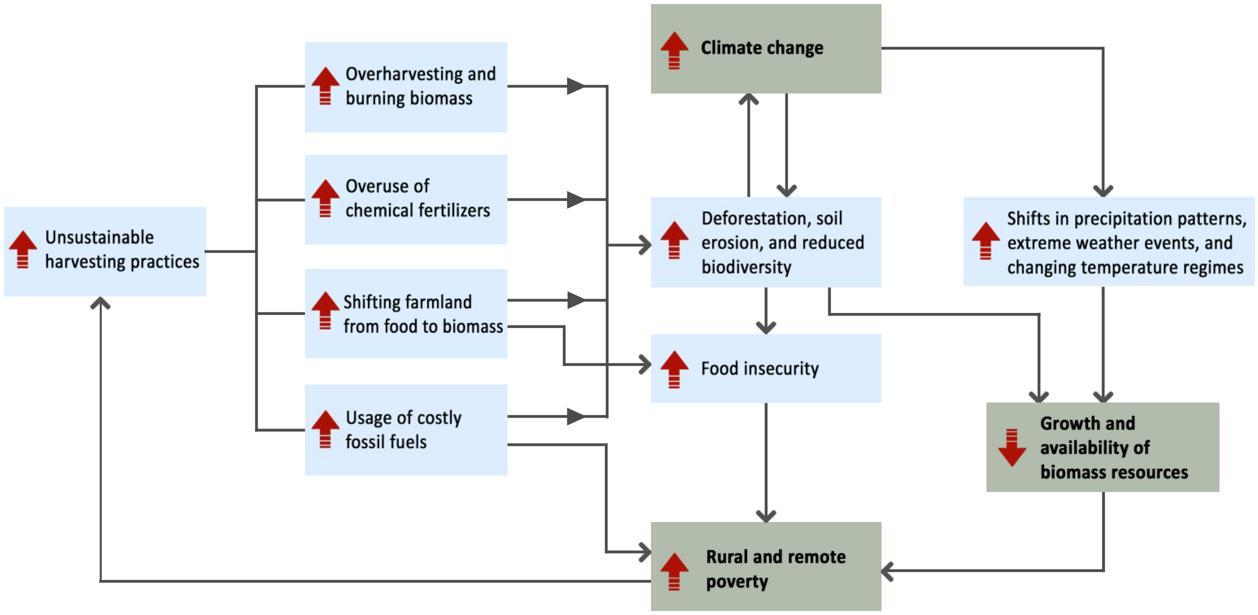

Fig. 4. Feedback loop illustrating the relationships between unsustainable harvesting practices, climate change, environmental repercussions, and rural poverty.

bioeconomy (Zabaniotou, 2018; Escalante et al., 2022; Ranjbari et al., 2022) or potential future foods (Zabaniotou, 2018). Harnessing marginalized or fallow lands for energy crop cultivation (Shortall, 2013) and transitioning to advanced-generation biofuels offer alternatives that sidestep food production interference (Nanda et al., 2018; Ahmed et al., 2021). Cutting-edge methodologies, such as advanced genetics (Harfouche et al., 2011) and selective breeding (Tester and Langridge, 2010), hold promise for augmenting biomass yields. Targeted policies that favor specific bioenergy feedstocks and deliberate land-use strategies are paramount in navigating the intricate food-fuel nexus (Muscat et al., 2020). Additionally, rural poverty can reduce the adaptive capacity of these communities. With limited resources and access to modern technologies or education, these communities are less equipped to innovate or adopt sustainable practices in the face of changing climatic conditions (Olsson et al., 2014). Reduced adaptive capacity means that even minor climate-induced changes can have severe repercussions for their livelihoods and well-being.

In essence, the convergence of climate change, biomass production, and rural poverty underlines the need for integrated, sustainable, and community-centered solutions. There is an undeniable imperative to address these intertwined challenges holistically, acknowledging the multi-faceted impacts on both the environment and human livelihoods. The chain reactions between these factors suggest that interventions in one area will undoubtedly ripple through the others.

3.4.2. The future of sustainable agriculture and farming practices

Innovative pretreatment technologies, including baling, pelletization/briquetting, and pyrolysis, optimize energy density in biomass (Albashabsheh and Stamm, 2021). Baling increases biomass bulk density, with rectangular bales favored for large-scale operations due to the ease of stacking (Albashabsheh and Stamm, 2021). However, flowable forms like pellets and briquettes are advantageous for a uniform biomass supply chain as they use existing grain transportation equipment (Albashabsheh and Stamm, 2021). Pyrolysis, involving heating biomass in an oxygen-free environment, stands out for achieving the highest densities and results in products like bio-oil, biochar, and synthesis gas (Albashabsheh and Stamm, 2021). These methods collectively address biomass logistical challenges, curbing transportation and storage costs.

Sustainable biomass production methods are gaining traction, heralding the rise of advanced bioenergy solutions, notably biodiesel (Hajjari et al., 2017) and biogas (World Bioenergy Association, 2013). Biodiesel, produced from vegetable oils, animal fats, and even algae, offers a cleaner alternative to traditional diesel, reducing GHG emissions and other pollutants. Its biodegradable nature and reduced sulfur content make it environmentally friendly, supporting the shift toward sustainable transportation (Hajjari et al., 2017). On the other hand, biogas—derived from the anaerobic decomposition of organic materials such as agricultural residues, manure, and wastewater sludge—provides a renewable energy source for heating, electricity generation, and vehicle fuel (World Bioenergy Association, 2013; Tabatabaei et al., 2020). By valorizing waste products, biogas production not only mitigates methane emissions, a potent GHG but also supports waste management and circular economy approaches (World Bioenergy Association, 2013; Tabatabaei et al., 2020). Integrating these advanced bioenergy methods within biomass production systems can bolster the sustainable energy portfolio, ensuring energy security, reducing environmental footprint and supporting rural economies.

Agroforestry is also a noteworthy solution (Faße et al., 2014; Mbow et al., 2014; Sharma et al., 2016). Beyond its power to sequester carbon by planting trees and shrubs, it enhances biodiversity by furnishing a mosaic of habitats for diverse species (Jose, 2009; Ramachandran Nair et al., 2009). Economically, it affords farmers a diversified income source: they can harvest fruits, nuts, or timber from the trees while cultivating crops on the same piece of land (Faße et al., 2014). Furthermore, the shade from these trees can protect understory crops, potentially reducing their water requirements and shielding them from extreme weather conditions.

Further, the cultivation of perennial crops has both environmental and economic advantages. A transition from annual to perennial crops results in an average increase of 20% in soil organic carbon (SOC) over a 20-year period at soil depths of 0–30 cm and a 10% increase over the 0–100 cm profile. This can contribute significantly to climate change mitigation (Ledo et al., 2020). In addition to increasing SOC stocks, perennial crops can reduce soil erosion, enhance food security, and offer higher plant residues than annual crops, which further contribute to soil carbon (Fernando et al., 2018; Ledo et al., 2020). However, the approach to managing perennial crops plays a crucial role in determining their environmental impact. For instance, burning plant residues at the end of the crop cycle may lead to GHG emissions that outweigh the carbon sequestration benefits during the crop's growth phase. On the other hand, using perennials in the restoration of degraded lands can bolster food security and local economies (Glover and Reganold, 2010; Ledo et al., 2020). A major economic and environmental advantage of perennial crops is that they do not need to be replanted annually, reducing the costs associated with seeds and sowing (Glover and Reganold, 2010).

3.4.3. International community initiatives and policy interventions

Financial backing and capacity-building are paramount in the global arena. Through financial outreach, countries can build resilient infrastructure, such as storage facilities in rural areas, which are key to reducing post-harvest losses. Such infrastructural advancements in rural regions can lead directly to rural poverty alleviation by providing stable food sources and generating local employment opportunities. Furthermore, by availing modern, environmentally friendly technologies to developing nations, these rural communities can transition to cleaner production methods without retracing the deleterious steps previously taken by industrialized nations. This not only supports sustainable biomass production but also revitalizes rural economies, offering a pathway out of poverty for many.

The international community's emphasis on sustainable biomass is evident in its advocacy for certification systems (Van Dam et al., 2008). Ensuring that biomass, especially biofuels, is produced in an environmentally benign manner preserves ecosystems. Moreover, adopting sustainable farming practices in rural settings, applicable to both biomass and cash crops, can enhance yields and profitability, directly mitigating rural poverty. Alongside this, trade incentives can coax countries into adopting sustainable biomass production practices, fostering a trajectory that intertwines green growth with rural economic development. Women, who are frequently the backbone of biomass-centric rural communities, must not be overlooked. Tailored training programs can boost their active participation in biomass production, processing, and decision-making echelons in these areas. By economically empowering women in rural settings, we further the goal of rural poverty reduction. International policies need to shift from mere acknowledgment to a tangible appreciation of the indispensable roles rural women play, from biomass gathering to its ultimate use.

Regional cooperation magnifies the effects of individual endeavors. Shared research between neighboring countries can tackle challenges common in rural areas, and harmonized policy directives can more aptly address issues such as the menace of transboundary air pollution from biomass combustion. Such combined efforts, in addition to championing sustainable practices, can stimulate regional rural economic growth and be pivotal in alleviating rural poverty.

3.4.4. Future needs for research

Enhancing biomass conversion efficiency remains a top research priority. Breakthroughs in stove design and biogas generation methods can elevate combustion efficiency, subsequently trimming down pollutants and related health hazards. Future research should delve into developing innovative, cost-effective, and sustainable storage solutions, especially for rural regions that are most impacted by post-harvest losses.

A holistic assessment of biomass sources requires comprehensive life cycle analyses. These studies will dissect the total environmental footprint of different biomass types from inception to consumption. While sustainable biomass is heralded for its eco-friendly benefits, it is imperative to continually monitor and evaluate its overall impact, especially on vital aspects like soil health, water quality, and biodiversity. The socioeconomic ramifications cannot be sidelined either. Research must intertwine the environmental advantages of sustainable biomass with the potential upliftment of rural economies. A deep dive into these dynamics will pave the way for interventions that can spur rural development and ameliorate poverty.

In the domain of agricultural research, the spotlight is on the development of climate-resilient crops. Cutting-edge techniques like genome editing, particularly CRISPR (clustered regularly interspaced short palindromic repeats) technology (Zaidi et al., 2020), promise crops that can weather the vagaries of extreme climate conditions, ensuring undeterred biomass yield. Beyond this, the multifaceted benefits of sustainable farming practices need more investigation, exploring not only their environmental gains but also their role in bolstering rural economies.

We must value and protect the rich knowledge that Indigenous communities possess. Their deep-rooted understanding of sustainable farming and using biomass is unique. Combining this traditional knowledge with modern science can create lasting, environmentally friendly solutions for our planet.

In essence, the path to a sustainable future is paved with advanced farming methods, global collaborative ventures, and relentless, focused research. Through these channels, we are not only addressing immediate challenges but also building a stronger, brighter tomorrow.

4. Conclusions

The present study explores a novel topic by investigating the profound connections between climate change, biomass production, and rural poverty, thereby underscoring the intricacies of our global ecosystem. Climate change, an undeniable existential threat, exacerbates challenges faced by vulnerable rural communities, pushing them deeper into the quagmire of poverty. For these communities, biomass production emerges not only as a sustainable energy alternative but also as a means to uplift their economic circumstances. Rural regions, often at the frontline of climate change's adverse effects, witness firsthand the importance of sustainable energy sources like biofuels (Sheelanere and Kulshreshtha, 2013). These eco-friendly alternatives offer resilience against the vagaries of a changing climate, ensuring a consistent energy supply and reduced dependency on traditional, environmentally detrimental fuels. The by-products of this transition — such as the development of modern storage infrastructures — have the added advantage of reducing post-harvest losses, directly benefiting rural economies.

Certification systems for sustainable biomass play a pivotal role in this matrix, guiding and standardizing biomass production. By fostering environmentally friendly production methods, they indirectly combat the repercussions of climate change, safeguarding fragile ecosystems that rural communities rely upon. The potential of trade incentives in promoting sustainable biomass cannot be understated. By encouraging nations to integrate green methodologies, these incentives support rural areas in their journey toward economic stability, ensuring that biomass production aligns with environmental and economic goals. Recognizing women's central role in biomass-centric communities is also crucial. Their involvement in biomass collection, processing, and utilization positions them as key players in both combating climate change and uplifting rural economies. By empowering them with decision-making roles and tailored training, we strengthen the link between biomass production and poverty alleviation. Transboundary air pollution from biomass combustion is a stark reminder of the shared responsibilities and challenges in this endeavor. Regional cooperation can foster shared solutions, ensuring that the benefits of biomass production are reaped without further accelerating climate change.

In sum, addressing climate change through sustainable biomass production offers a two-fold solution: curtailing environmental degradation and providing a robust framework for rural poverty alleviation. The intertwined nature of these challenges and solutions beckons a holistic approach, harmonizing ecological responsibility with socio-economic advancement.

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