

Global climate action toward net-zero emissions: Pathways, technologies, challenges, and future directions

Hamed Kioumarsi ^{1*} , Marc A. Rosen ² , Bahareh Rafiei ³ , Zary Shariman Yahaya ⁴ , Reza Naseri Harsini ¹ , Hanif Amrulloh ⁵ , Hassan Gholipour Fereidouni ⁶ 

¹ Animal Science Research Department, Gilan Agricultural and Natural Resources Research and Education Center, AREEO, Rasht, IRAN

² University of Ontario Institute of Technology, Oshawa, ON, CANADA

³ Plant Protection Research Department, Gilan Agricultural and Natural Resources Research and Education Center, AREEO, Rasht, IRAN

⁴ School of Biological Sciences, Universiti Sains Malaysia, Penang, MALAYSIA

⁵ Universitas Ma'arif Lampung, Metro, INDONESIA

⁶ School of Business, Western Sydney University, Parramatta, NSW, AUSTRALIA

*Corresponding Author: hkioumars@yahoo.com

Citation: Kioumars, H., Rosen, M. A., Rafiei, B., Shariman Yahaya, Z., Naseri Harsini, R., Amrulloh, H., & Gholipour Fereidouni, H. (2026). Global climate action toward net-zero emissions: Pathways, technologies, challenges, and future directions. *European Journal of Sustainable Development Research*, 10(3), em0407. <https://doi.org/10.29333/ejosdr/18611>

ARTICLE INFO

Received: 19 Feb. 2026

Accepted: 05 May 2026

ABSTRACT

The review presents a thorough overview of international climate change initiatives which include specific methods to achieve net-zero greenhouse gas (GHG) emissions. The study assesses climate change scientific evidence by explaining why net-zero targets need to be achieved and it examines major international climate action frameworks and policy mechanisms. The article investigates new technologies which help decrease carbon emissions throughout various essential industrial areas while describing current methods to measure progress and assess climate change initiatives. The study examines multiple factors which prevent organizations from reaching net-zero emissions targets by investigating policy uncertainty technological constraints, and financial limitations and equity considerations. The study investigates how agriculture and animal husbandry activities generate GHG emissions while showing which climate-smart solutions and technological advancements and improved governance practices can help reduce emissions. The review establishes essential research areas which require further study because integrated cross-sectoral strategies need to achieve both mitigation and sustainable development goals. The article presents multiple future climate options which will help policymakers and industry leaders and stakeholders reach international climate targets while creating a sustainable transition system for net-zero emissions.

Keywords: climate action, net-zero emissions, decarbonization pathways, climate change mitigation, sustainable agriculture

INTRODUCTION

Human activities lead to greenhouse gas (GHG) emissions which are the main cause for climate change. The international community requires immediate climate action which needs coordinated efforts to achieve net-zero emissions in order to prevent global warming and its extensive environmental and social and economic impacts. International climate goals depend on net-zero strategies because these approaches enable countries to control GHG emissions through natural and technological methods which lead to stable atmospheric GHG levels. The review presents current scientific knowledge about climate action programs which include net-zero emissions science and current progress and major obstacles and future research paths (United Nations [UN], 2021). While numerous review studies have examined climate change

mitigation pathways and net-zero strategies, many of them focus on individual sectors, specific technologies, or policy instruments in isolation. In contrast, this review adopts an integrated cross-sectoral perspective that simultaneously examines energy systems, industrial processes, agricultural and livestock systems, and governance frameworks. Furthermore, this study places particular emphasis on implementation challenges, monitoring and accountability mechanisms, and the role of agriculture and animal husbandry—areas that are often underrepresented in existing literature. This integrated approach provides a more comprehensive understanding of the practical barriers and opportunities associated with achieving net-zero emissions. The current worldwide emission patterns do not match the necessary pathways which need to be followed for keeping temperature increases below 1.5 °C. The Intergovernmental Panel on Climate Change (IPCC) states that mid-century

global net-zero CO₂ emissions must be reached to protect against the most dangerous and permanent climate effects (IPCC, 2022, 2023). In alignment with the IPCC AR6 framework, this study explicitly adopts the shared socio-economic pathway SSP1-1.9 as the primary reference scenario for achieving the 1.5 °C target. This scenario represents a sustainability-oriented pathway characterized by rapid decarbonization, strong international cooperation, and accelerated technological innovation. Accordingly, the carbon budget estimates discussed in this review, including the approximately three-year remaining emissions window, are interpreted within the SSP1-1.9 context rather than as general projections.

This framing ensures that the carbon budget analysis is consistent with scenario-based integrated assessment models used in IPCC AR6, enhancing the robustness and policy relevance of the presented projections.

Human activities that include fossil fuel combustion and land-use change have caused global temperatures to rise and precipitation patterns to shift and extreme weather events to become more common since the mid-20th century. The scientific community has reached a uniform agreement that human-produced GHG emissions constitute the main factor behind the planet's current warming trend. The changes present major dangers to agricultural production and species diversity and public health and economic systems because they endanger food and water supplies and speed up the loss of biodiversity and worsen health problems that depend on climate conditions. Economic evidence demonstrates that delayed climate action results in higher long-term mitigation and adaptation expenses while early investments in decarbonization produce significant economic and social benefits that include job creation and better public health and stronger energy security (International Monetary Fund [IMF], 2022; OECD, OECD, 2024; Stern, 2006).

The Paris agreement establishes 1.5 °C as the maximum allowable temperature increase above pre-industrial levels which countries must achieve by implementing mitigation efforts that reduce GHG emissions while increasing carbon sink capacity to reach a balance between emissions and emissions removal. The transition to net-zero emissions requires complete transformation of all energy systems and transportation networks and industrial operations and land-use practices which will be achieved through technological advancements and policy changes and shifts in human behavior. Climate projections predict that without immediate action the world will experience severe and almost unchangeable effects which demonstrate the necessity for organizations to combine their climate change mitigation efforts with their climate change adaptation programs as part of their overall sustainability initiatives (Abbass et al., 2022; Dablander et al., 2024; IPCC, 2013).

Recent studies show that effective climate solutions require simultaneous funding for climate adaptation and equity-based policies. Sustainable net-zero pathways need integrated approaches which include climate justice and just transition principles together with protection of vulnerable communities (IPCC, 2022; Newell & Mulvaney, 2013; United Nations Framework Convention on Climate Change [UNFCCC], 2023). The research now focuses on how multilevel

governance, corporate climate commitments, and non-state actors contribute to climate action progress. The rapid growth of voluntary initiatives and corporate net-zero pledges faces challenges related to their enforcement and public visibility and their ability to verify emissions reduction claims (Fankhauser, 2022; Science Based Targets initiative [SBTi], 2023; UNFCCC, 2023).

The objectives of this review are to synthesize the scientific, technological, and policy literature related to global climate action toward achieving net-zero GHG emissions. This includes examining key international frameworks and decarbonization pathways across major sectors such as energy systems, transportation, industrial processes, and agriculture. In addition, the review explicitly incorporates adaptation considerations where relevant—particularly in relation to climate resilience, agricultural systems, and policy frameworks—in order to provide a more integrated and systems-oriented perspective on climate action. The study also aims to identify key research gaps and future priorities for achieving sustainable and equitable net-zero transitions.

METHODOLOGY

The study uses an integrative review method to combine existing research about global climate action and net-zero GHG emission pathways. The integrative approach was chosen to enable researchers to assess evidence from multiple sources which included climate science and policy analysis and technological innovation and sectoral studies to create a comprehensive assessment of all mitigation strategies and governance frameworks and implementation challenges.

Literature Search Strategy

The researchers performed a systematic literature review which used major academic databases, such as Web of Science and Scopus and Google Scholar, to achieve complete identification of all valid peer-reviewed studies. The research team conducted a systematic review of authoritative reports and assessments from international institutions which included the IPCC and UN and United Nations Environment Program (UNEP) and Organisation for Economic Co-operation and Development (OECD) and World Economic Forum (WEF) to obtain current policy-relevant information. Search queries combined relevant keywords and Boolean operators, including: “climate action,” “net-zero emissions,” “decarbonization pathways,” “greenhouse gas mitigation,” “climate governance,” “energy transition,” “agriculture and livestock emissions,” and “sustainable development.” Forward and backward citation tracking was also used to identify additional influential studies. Although Google Scholar was used to ensure comprehensive coverage of the literature, additional filtering criteria were applied to maintain the scientific quality of the review. Specifically, only peer-reviewed journal articles, highly cited publications, and reports from reputable international organizations were included. Grey literature was carefully screened and included only if it originated from authoritative sources such as IPCC, OECD, UN agencies, and other recognized institutions. Duplicate records were removed, and studies lacking

methodological rigor or relevance to net-zero pathways were excluded. This approach ensured both comprehensiveness and quality control in the literature selection process. This study follows the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines to ensure transparency and reproducibility in the literature selection process. A PRISMA flow diagram has been included to illustrate the identification, screening, eligibility, and inclusion of studies.

Inclusion and Exclusion Criteria

Publications were included based on the following criteria: The research used

- (1) peer-reviewed papers which appeared mainly in Q1-rank journals that Web of Science and Scopus databases had indexed,
- (2) high-impact global or regional reports from reputable international organizations,
- (3) which contained direct links to climate change mitigation and net-zero targets and sectoral transition pathways and policy and governance mechanisms, and
- (4) which could be read in English.

While priority was given to high-impact studies published in Q1-ranked journals to ensure scientific rigor, relevant and high-quality studies from Q2 and Q3 journals were also considered where they provided important or emerging insights into net-zero technologies, sectoral transitions, or policy developments. This approach allowed for a balance between quality assurance and inclusiveness of recent advancements in the field.

The study excluded research which did not show direct connection to net-zero goals and climate action objectives and who studied only specific communities without proving their results could apply to other areas. To ensure the quality and reliability of the included studies, a structured quality assessment approach was applied. Studies were evaluated based on criteria such as publication in peer-reviewed journals, methodological rigor, clarity of research design, relevance to net-zero and climate action pathways, and citation impact. In addition, reports from reputable international organizations (e.g., IPCC, OECD, and UN agencies) were included based on their institutional credibility. Studies that lacked methodological transparency, sufficient data support, or direct relevance to the research objectives were excluded. Although a formal scoring tool (e.g., CASP) was not applied, a consistent qualitative assessment framework was used to minimize selection bias.

This study was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, reproducibility, and methodological rigor in the literature selection process. The review followed a structured multi-stage procedure, including identification, screening, eligibility assessment, and final inclusion of studies. A PRISMA flow diagram (Figure 1) is provided to illustrate the systematic process of study selection, including database searches, removal of duplicates, screening of titles and abstracts, and full-text eligibility assessment. This approach enhances the traceability and robustness of the review methodology.

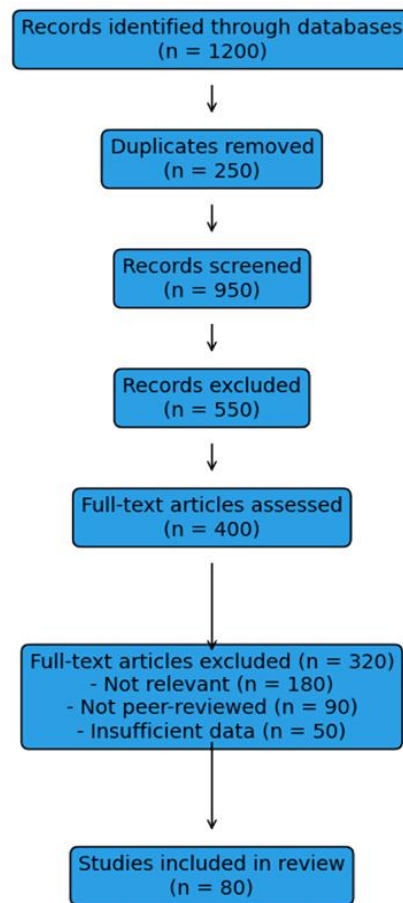


Figure 1. PRISMA flow diagram illustrating the systematic literature selection process, including identification, duplicate removal, screening, full-text eligibility assessment, and exclusion with reasons, followed by final inclusion of studies (Source: Authors' own elaboration)

Scope and Analytical Framework

The literature review examined various fields of study which include climate science, energy systems, environmental economics, public policy, agriculture, and sustainability research. A thematic analytical framework was applied to organize and interpret findings across core domains which included scientific foundations of climate change and net-zero emissions, global climate governance and policy frameworks, technological and sectoral pathways toward decarbonization, progress tracking and indicators, sector-specific insights, particularly in agriculture and animal husbandry, and systemic barriers to implementation. Following the identification of relevant studies, a structured qualitative thematic analysis was conducted to systematically extract and synthesize key information. Data extraction focused on core dimensions including mitigation strategies, technological pathways, sectoral applications, policy frameworks, and implementation challenges. The selected studies were coded and categorized into thematic groups, enabling comparative analysis across sectors such as energy, industry, transportation, and agriculture. A narrative synthesis approach was then applied to integrate findings from diverse study designs, identify common patterns, highlight divergences, and reveal emerging trends. This methodological approach ensured a comprehensive and systematic interpretation of the literature.

Synthesis Approach

The researchers conducted a qualitative narrative synthesis to unify evidence from studies that used different research designs and various research methods. The synthesis established three main findings which included common results and opposing viewpoints and new research developments and essential study requirements. The climate action strategies were assessed according to their effectiveness and limitations and future development possibilities which followed high-impact review article standards.

SCIENTIFIC FOUNDATIONS OF CLIMATE CHANGE AND NET-ZERO EMISSIONS

Scientific evidence demonstrates that anthropogenic GHG emissions—primarily from fossil fuel combustion, industrial processes, and land-use change—are the dominant drivers of observed global warming. Since the pre-industrial era, global average temperatures have risen by approximately 1.2 °C, accompanied by significant changes in precipitation patterns, sea-level rise, and the increasing frequency of extreme weather events. These trends highlight the growing pressure on Earth systems and the heightened risk of irreversible climate impacts. Within this context, the concept of the global carbon budget has emerged as a critical framework for quantifying the remaining allowable emissions to limit warming to 1.5 °C. Current estimates indicate that this budget is rapidly diminishing, underscoring the urgency of immediate and sustained emissions reductions to avoid crossing critical climate thresholds (IPCC, 2022, 2023).

A critical concern in current net-zero strategies is the increasing reliance on carbon dioxide removal (CDR) technologies that remain technologically uncertain and economically constrained on scale. Approaches such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) are often embedded in long-term mitigation scenarios, yet their large-scale deployment faces significant challenges related to cost, energy demand, land use, and environmental impacts. Over-reliance on these unproven technologies introduces substantial risks, as it may delay immediate emission reductions and create unrealistic expectations regarding future mitigation capacity. Therefore, current scientific consensus emphasizes that CDR should complement—rather than substitute—aggressive near-term emission reductions.

A critical component of scientifically credible net-zero strategies is the hierarchy of mitigation, which prioritizes direct emission reductions (abatement) over CDR. In this framework, emission reductions across all sectors must be maximized before relying on carbon removal approaches to offset residual emissions. This distinction is essential to prevent the overuse of offsetting mechanisms and to ensure that net-zero targets reflect real and sustained emissions declines rather than accounting-based neutrality. Over-reliance on carbon removal technologies may undermine mitigation efforts, particularly given the uncertainties associated with their scalability, permanence, and environmental impacts.

The worldwide climate policy framework has established net-zero emissions as its primary goal since this scientific framework emerged. Net-zero refers to a state in which human GHG emissions balance out through natural sinks and technological solutions, which leads to zero increase in atmospheric GHG levels. The process of achieving net-zero requires extensive emissions cuts from every sector instead of complete emission termination while using legitimate carbon removal methods to counterbalance remaining emissions. The IPCC states that worldwide CO₂ emissions must reach net-zero by approximately 2050 to achieve temperature stability and reduce major climate change effects (IPCC, 2022).

The process of achieving net-zero emissions must be understood as something distinct from both carbon neutrality and climate neutrality. Carbon neutrality requires the balance of CO₂ emissions through offsetting methods which only address carbon dioxide emissions, while climate neutrality requires the evaluation of all GHGs and their comprehensive climate effects. Scientific targets form the foundation of net-zero frameworks which establish guidelines for organizations to cut emissions through direct methods while permitting offsets only for emissions that remain after all practical abatement efforts. The separation of these two elements serves as an essential factor which maintains the environmental authenticity and trustworthiness of net-zero commitments according to Fankhauser et al. (2022).

Observations up to 2025 indicate that global mean surface temperatures have persistently exceeded 1.5 °C above pre-industrial levels, mainly due to fossil fuel emissions and land-use change. Current record-high emissions are further amplifying warming, ocean heat accumulation, sea-level rise, and extreme weather events. The latest estimates of the global carbon budget indicate that the remaining budget to keep warming below 1.5 °C with a probability of 50 % is about 130 billion tonnes of CO₂ from the beginning of 2025, which is equivalent to about three years of current emissions. For a two-thirds probability of remaining below 1.5 °C, the remaining budget is even more constrained, potentially less than two years. Even when considering the uncertainties in climate sensitivity and non-CO₂ forcing, current estimates indicate that the probability of passing 1.5 °C is increasingly likely unless immediate and deep global emissions cuts are made. Carbon budgets for higher warming levels of 1.7-2 °C are only slightly longer, emphasizing the short time frame for effective mitigation (Friedlingstein et al., 2025; World Meteorological Organization [WMO], 2025).

The scientific basis for net-zero pathways becomes stronger through evidence which shows that continuous early mitigation work leads to decreased future risks and reduced total expenses. Studies show that when emissions are reduced quickly during the next decade, the need for CDR systems decreases, which will become necessary in the future but their functional abilities and environmental effects remain unknown. The science-based net-zero strategies require organizations to implement immediate changes while transforming their systems and achieving farther-reaching sustainability goals and equity targets. The scientific foundations establish strong evidence which demonstrates that net-zero emissions have become a fundamental element of international climate policy and that complete climate

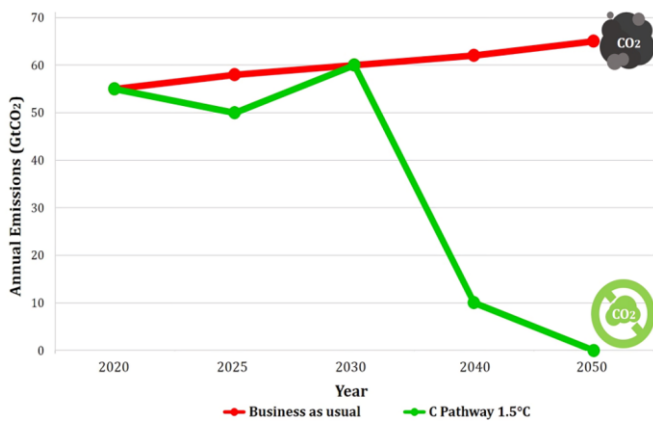


Figure 2. Comparative projection of global GHG emissions: BAU scenario vs. the 1.5 °C-consistent net-zero pathway by 2050 (IPCC, 2023)

solutions need to be implemented without delay. The following sections will explore global governance systems and their impact on various sectors and technological advancements and the challenges which impede progress toward achieving net-zero emissions.

As illustrated in **Figure 2**, there is a significant ‘emissions gap’ between current national commitments and the required scientific pathways. While the business-as-usual (BAU) scenario leads to continued warming, the net-zero pathway necessitates a sharp decline in emissions by 2030, highlighting the urgency of immediate policy interventions and rapid decarbonization.

GLOBAL CLIMATE ACTION FRAMEWORKS AND GOVERNANCE

The multi-level system which manages global climate action operates through international agreements and national policies and local implementation efforts. The UNFCCC serves as the international framework that enables countries to work together on climate issues while the Paris Agreement functions as the main component of worldwide climate governance. Countries use nationally determined contributions (NDCs) to fulfill their Paris framework obligations which require them to keep global temperature rise under 2 °C while trying to achieve 1.5 °C limits (IPCC, 2022; UNFCCC, 2015). The current NDCs which all countries participate in fail to establish emissions pathways that would enable worldwide compliance with the 1.5 °C climate agreement target. The Global Stocktake assessments show continuing gaps in both ambition and implementation which require urgent emissions reductions and improved governance systems to convert political promises into tangible results (UNEP, 2023; UNFCCC, 2023). The research demonstrates that voluntary commitments lack effectiveness because they need both strong accountability measures and enforcement systems to function properly. The decarbonization process depends on national and regional policy instruments which include carbon pricing and renewable energy targets and efficiency standards and climate-related disclosure requirements and international treaties. The three factors which include institutional capacity

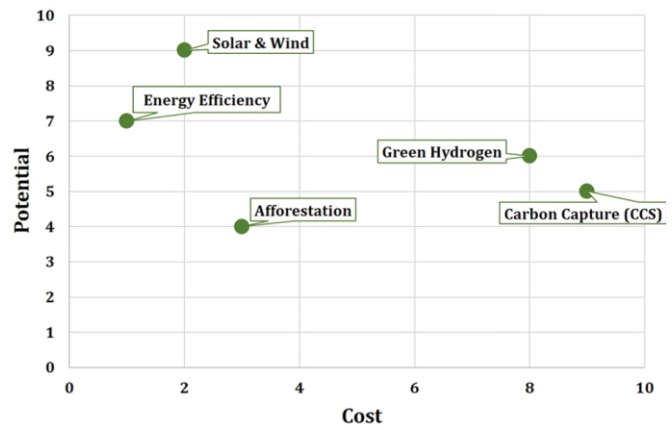


Figure 3. Cost-benefit analysis of key decarbonization technologies, mapping their mitigation potential against implementation difficulty and economic cost (IEA, 2023)

and economic conditions and political stability determine how effective policies will perform their intended functions while the two factors of fossil fuel subsidies and regulatory inconsistencies act as primary obstacles to major mitigation initiatives (OECD 2024).

Non-state actors have gained additional power through corporate net-zero commitments and scientific target requirements and financial reporting, which enable them to drive climate initiatives outside of government control. The SBTi has enhanced climate science alignment through its programs, yet organizations still face problems with transparent operations and accountable practices and their excessive dependence on carbon offsets for voluntary agreements (Fankhauser et al., 2022). Effective climate governance requires multiple governance levels to work together for achieving international goals. The successful implementation of climate commitments depends on enhancing policy coherence and stakeholder involvement and establishing effective monitoring and reporting and verification (MRV) systems.

PATHWAYS AND TECHNOLOGIES TOWARD NET-ZERO EMISSIONS

To reach net-zero GHG emissions all sectors must undergo substantial changes through coordinated efforts which include energy systems and industrial processes and transportation and building operations and land-use management. Scientific assessments consistently demonstrate that no single technology or policy instrument can achieve net-zero emissions by itself; instead, multiple mitigation pathways together with enabling technologies are required to achieve long-term emissions reductions that support both economic growth and human welfare (IPCC, 2022). Strategic prioritization of technologies is essential for cost-effective transitions.

Figure 3 identifies ‘low-hanging fruit’ solutions like energy efficiency and renewable, while positioning carbon capture and storage (CCS) as a high-potential but high-cost necessity for hard-to-abate sectors.

Energy System Transformation

The process of energy system decarbonization serves as the fundamental element for achieving net-zero emissions pathways. The most effective and economically viable solution for reducing carbon emissions involves two key actions, which are rapid adoption of renewable energy sources and electrifying all end-use sectors. Energy efficiency enhancements in building structures and industrial facilities and transportation systems lead to reduced energy consumption, which results in diminished requirements for supply-side capacity expansion. The growing adoption of variable renewable energy sources requires additional technologies, such as grid updates and energy storage facilities and demand-side management systems, which help maintain system operational reliability and resilience (International Energy Agency [IEA], 2023; IPCC, 2022).

Industrial Decarbonization and Carbon Capture

Net-zero transitions face major obstacles in cement steel chemical and aviation sectors because these industries depend on fossil fuels and emit GHGs through their operational processes. The sector uses CCS technology together with low-carbon hydrogen fuel switching and material efficiency methods to achieve critical operational objectives. CCS systems serve as necessary tools to handle onsite emissions at industrial sites which need to control their remaining emissions though they should not function as complete solutions for emission control according to existing regulations and planned storage safety systems (IEA, 2023; Rogelj et al., 2018).

Despite its recognized role in decarbonizing hard-to-abate sectors, the large-scale deployment of CCS remains constrained by significant economic, technical, and infrastructural challenges. Current CCS projects are limited in number and scale, and their widespread adoption is hindered by high capital costs, substantial energy requirements, and the need for extensive CO₂ transport and storage infrastructure. Moreover, uncertainties related to long-term storage safety and public acceptance further complicate large-scale implementation. Therefore, while CCS is considered a necessary component of net-zero pathways, its role should be viewed as complementary rather than a primary mitigation strategy, particularly in the near term. Recent pilot projects (2024-2025) indicate slower-than-expected deployment rates, reinforcing concerns about scalability.

It is important to distinguish between energy-related emissions and process-related emissions when analyzing industrial decarbonization pathways. In sectors such as steel production, a significant portion of emissions arises from energy use, allowing for mitigation through electrification (e.g., electric arc furnaces) or hydrogen-based direct reduced iron processes. In contrast, cement production generates substantial process emissions from the calcination of limestone, which cannot be eliminated through fuel switching alone and therefore requires alternative approaches such as carbon capture technologies or material substitution. Similarly, aviation and chemical industries present distinct challenges due to their reliance on energy-dense fuels and complex production chains. This differentiation highlights the

need for sector-specific mitigation strategies rather than a one-size-fits-all approach.

Hydrogen and Emerging Energy Carriers

Low-carbon hydrogen has become an important energy source because it enables decarbonization efforts across industrial and transportation and energy storage sectors. The green hydrogen that comes from renewable electricity and the blue hydrogen with its CCS technology create emission reduction options for sectors that cannot use direct electrification. The hydrogen deployment process requires three essential elements which include decreasing costs, building necessary infrastructure and establishing unambiguous policy frameworks that will drive investment and market development (IEA, 2023; OECD, 2024).

Built Environment and Urban Systems

The built environment accounts for a large portion of worldwide energy use and GHG emissions, which makes it essential for net-zero planning. Low carbon building construction operates through building envelope upgrades and energy-efficient system installation and building electrification and renewable energy deployment. Urban planning approaches that promote compact development and sustainable mobility and nature-based solutions create extra climate mitigation benefits through improved air quality and public health and climate resilience (IPCC, 2022).

Nature-Based Solutions and Carbon Removal

Net-zero pathways need CDR as their main method to subtract leftover emissions after achieving their required emission reductions. Nature-based solutions which include afforestation and reforestation and ecosystem restoration and soil carbon sequestration provide affordable climate mitigation methods that also bring extra benefits for biodiversity and local communities. The technological CDR methods which include DAC and BECCS provide potential net-zero solutions for the upcoming decades. The scientific world currently investigates and debates the environmental effects and governance problems and scalability issues of these technologies (IPCC, 2022; Smith et al., 2023). Net-zero pathways achieve their maximum effectiveness through the combined use of new technological solutions and existing supportive policy frameworks and changes in social behavior. The diverse regional differences in resources and socioeconomic factors and institutional capacity requirements make it necessary to use adaptable methods which match the specific needs of each situation to achieve successful mitigation pathways that support sustainability and equity throughout the entire process.

While BECCS is often highlighted as a promising carbon removal strategy, its large-scale deployment raises significant sustainability concerns. Extensive land requirements for biomass production may lead to competition with food systems, deforestation, and biodiversity loss, potentially undermining broader environmental and social objectives. Therefore, the implementation of BECCS must be carefully managed within sustainability and land-use constraints.

Similarly, DAC technologies, although conceptually attractive, remain limited by high energy requirements and

substantial costs. Recent estimates suggest that DAC costs currently exceed \$500-600 per ton of CO₂ captured, making large-scale deployment economically challenging in the near term. These limitations highlight the need for continued technological innovation and caution against over-reliance on DAC as a primary mitigation pathway.

TRACKING CLIMATE ACTION PROGRESS AND INDICATORS

The evaluation of policy effectiveness and technological performance and governance system effectiveness requires climate action progress monitoring and net-zero emission tracking. The tracking system provides transparent information which enables policymakers and investors and stakeholders to assess current actions against climate targets while the system helps them create new strategies to address upcoming challenges. The only way to implement net-zero commitments is through effective monitoring systems which allow organizations to turn their goals into practical actions.

Global Emissions Trends and Climate Indicators

Current studies show that GHG emissions keep increasing worldwide, which happens despite stronger political promises and better technological solutions. The Earth system shows signs of moving beyond its stable climate condition because atmospheric CO₂ levels and global average surface temperatures and ocean heat content and sea-level rise and extreme weather event frequency all show increasing trends. The annual update of global climate indicators shows that recent years have recorded the highest temperatures, which creates an urgent need to speed up mitigation work (IPCC, 2023).

Measurement, Reporting, and Verification Frameworks

The climate action depends on measurement systems which establish transparent reporting procedures and verification processes to maintain accountability through their measurement work. The MRV system provides national GHG data which documents progress toward NDCs while supporting international Global Stocktake assessment processes. Current remote sensing technology together with digital monitoring systems and standardized accounting methods enables more precise and comparable emissions data assessment. The developing regions of the world (UNFCCC, 2023) face ongoing challenges because different countries experience varying levels of technical expertise and access to data.

Recent advances in digital monitoring technologies have significantly enhanced the accuracy and transparency of emissions tracking. Satellite-based monitoring systems now enable near real-time detection of GHG emissions, particularly methane (CH₄) leaks from energy infrastructure, providing unprecedented spatial and temporal coverage. In parallel, artificial intelligence (AI) and machine learning techniques are increasingly used to analyze large-scale environmental datasets, improve emissions estimation, and support predictive modeling. These innovations strengthen MRV systems by enabling more reliable, data-driven, and scalable monitoring of climate action progress.

Corporate and Financial Disclosure Mechanisms

Climate action tracking now depends more on corporate and financial sector climate data than on national reporting requirements. The climate-related financial disclosures system and science-based targets framework have experienced rapid expansion because organizations now recognize climate-related risks and opportunities. Environmental social governance metrics now serve as standard tools for evaluating corporate climate performance which investors use to make their investment choices. The existing data inconsistency problems and greenwashing practices together with corporate emissions reduction pledges that fail to match actual emissions reductions present a demand for stronger standards and independent verification (Fankhauser et al., 2022; OECD, 2024).

Regional and Sectoral Progress Assessment

Climate action in different areas and industry segments shows inconsistent progress toward achieving net-zero emissions targets. Some regions have successfully cut their emissions intensity through renewable energy projects and efficiency work, but other areas still rely on fossil fuels for their energy needs. Power generation has progressed more quickly than transport and industrial and agricultural sectors because of existing structural and technological challenges. The existing differences in the data require development of specific tracking systems which will accurately capture the unique characteristics of each sector and each geographic area (IEA, 2023).

Integrating Mitigation and Adaptation Metrics

The recent research shows that climate action progress requires matching mitigation and adaptation indicators to create complete evaluation systems. Emission metrics function as mitigation measurement tools but adaptation indicators serve to show resilience and vulnerability reduction and climate impact preparedness. The integration of these elements allows for complete climate strategy assessment while achieving sustainable development goals (IPCC, 2022). The effective net-zero pathways of climate action tracking systems depend on trustworthy indicators which enable transparent reporting of their progress. The climate commitments need data quality improvements together with standardized methods and increased monitoring abilities which should lead to actual emissions reductions.

AGRICULTURE AND ANIMAL HUSBANDRY IN NET-ZERO PATHWAYS

Agriculture and animal husbandry play a dual role in the global transition toward net-zero GHG emissions. The sector generates significant emissions through CH₄ produced during enteric fermentation and nitrous oxide (N₂O) released from fertilized soils while the sector possesses considerable ability to reduce climate change impacts through carbon sequestration and sustainable land management and climate-smart practices. Integrated net-zero strategies depend on agriculture because they provide essential food security and supports rural communities and drives economic growth.

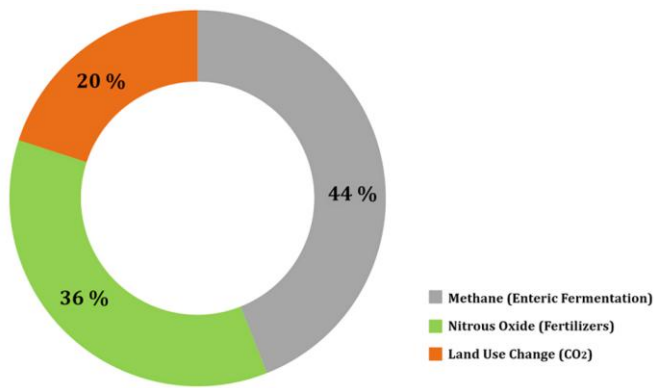


Figure 4. Breakdown of agricultural GHG contributions by gas type, emphasizing the dominance of methane and nitrous oxide in livestock and crop systems (FAO, 2023)

Emissions Profile and Climate Impacts

Agriculture contributes approximately 20-25% of global anthropogenic GHG emissions when land-use change is included, with livestock production accounting for a large share of CH₄ emissions. The short atmospheric lifespan of CH₄ compared to carbon dioxide allows for effective livestock system emissions reduction which creates significant climate advantages. The persistent problems caused by N₂O emissions from fertilizer application and manure management occur because of their long atmospheric lifespan and their ability to create greenhouse warming effects (IPCC, 2022; Kioumarsis et al., 2026; Rosen et al., 2025). Climate change enables agricultural systems to face serious threats because it changes temperature patterns and alters rainfall distribution and increases extreme weather occurrence. The alterations in climate patterns create risks for crop production and livestock yields and ecosystem functions which result in greater food shortages and reduced safety for people especially in developing areas. Agricultural mitigation strategies require implementation together with adaptation measures because this combined approach will create systems that remain stable while protecting the environment into the future.

Agriculture presents a unique challenge in net-zero strategies. As shown in **Figure 4**, non-CO₂ gases (CH₄ and N₂O) constitute the majority of the sector's footprint. This underscores the need for CH₄-specific mitigation strategies, such as improved enteric fermentation management and precision fertilization, rather than focusing on carbon dioxide alone.

Mitigation Strategies in Livestock and Crop Systems

The study identified numerous ways to decrease agricultural and livestock-related emissions through its research findings. Livestock systems can achieve substantial CH₄ emission reductions through the implementation of improved feed quality and dietary supplements and feed additives and enhanced herd management and productivity-based breeding methods. The agricultural sector reduces emissions through technological innovations that include precision feeding systems and anaerobic digestion of manure and renewable energy-powered farm operations which also enhance resource efficiency (Smith et al., 2024). The agricultural sector uses crop-based mitigation strategies which

combine optimal fertilizer usage with conservation tillage and crop rotation and better soil management methods to increase soil carbon storage capacity. The agricultural sector utilizes precision agriculture technologies which use digital tools and AI to optimize input usage for emission reductions and productivity maintenance. The agricultural industry develops systems which produce low emissions while operating at high efficiency through these combined practices.

Carbon Sequestration and Nature-Based Solutions

The agricultural sector provides essential natural solutions through its capacity to sequester carbon in soils and implement agroforestry practices and restore ecosystems. Land management improvements enable enhanced carbon storage in both soil and biomass, which helps reduce emissions from other sectors. The various approaches provide biodiversity advantages and water retention benefits and soil health improvements, although their carbon sequestration capacities depend on regional factors and management methodologies. The system's effectiveness requires persistent monitoring, which enables protection of permanent assets while preventing land-use conflicts (IPCC, 2022; World Economic Forum et al., 2025).

Pest Dynamics Under Climate Change and Net-Zero Agriculture

Climate change is changing how agricultural insects appear and spread and damage crops which creates more threats to food security and sustainable farming practices. Pest organisms experience changes in their life cycles and survival abilities and their spread capacity because of rising temperatures and changing precipitation patterns and increasing climate variability which results in more intense pest control challenges and the development of new pest species. The research shows that climate warming has already caused worldwide agricultural losses from insect pests which particularly affects major staple crops (Deutsch et al., 2018; Rafiei, 2025). The modifications lead to fundamental changes which affect the methods used to achieve net-zero agricultural targets. Pesticide usage increases because farmers face more severe pest problems which then leads to higher GHG emissions from both agrochemical production and their application, along with negative effects on biodiversity and ecosystem services. Uncontrolled pest populations will disrupt agricultural operations which rely on both climate change mitigation and adaptation strategies (IPCC, 2022). Climate-smart pest control methods help farmers achieve their net-zero goals while maintaining their crop yields. The Integrated Pest Management system together with biological control methods and crop diversification and precision agriculture technologies enables farmers to manage pest problems without needing to use chemical pesticides that produce high emissions. The strategies support system resilience while decreasing emissions and developing sustainable low-carbon food systems that operate under climate changes (Bebber et al., 2013). Sustainable pest management needs to be included in net-zero agricultural systems because it helps to decrease climate-related yield losses and cuts emissions and builds food system resilience against climate change.

Policy Frameworks and National Initiatives

Policy support functions as an essential requirement which agricultural mitigation and adaptation efforts need to achieve their full potential. National and regional initiatives increasingly emphasize climate-smart agriculture, CH₄ reduction, and innovation adoption. Canada's net-zero accountability act and agricultural CH₄ reduction initiatives demonstrate how regulatory frameworks and financial incentives and research investments enable livestock and crop systems to achieve emissions reductions. The research shows three challenges which need resolution before organizations can adopt climate measurement standards while establishing climate goals and food security and rural development objectives (Mahdavian et al., 2024).

Challenges and Trade-Offs

The agricultural sector has multiple obstacles which prevent it from reaching net-zero emissions despite its capacity to decrease emissions. The three main challenges which prevent emission reduction progress are financial and technological access difficulties, farm-level data variability and emissions estimation tool problems, and equity and livelihood protection concerns. The management of emissions reduction efforts must occur through controlled processes which preserve both agricultural output and environmental resources and farm soil health. Integrated agricultural systems which include technological breakthroughs and supportive government policies and farmer participation and sustainable development goal alignment are essential for achieving net-zero agricultural systems. The agricultural and livestock sectors must achieve net-zero emissions to meet their essential requirement while creating new possibilities. The sector will achieve its climate targets through mitigation technologies which enhance carbon sequestration and the implementation of enabling policies. The sector will achieve its climate targets through mitigation technologies which enhance carbon sequestration and the implementation of enabling policies.

BARRIERS AND SYSTEMATIC CHALLENGES TO ACHIEVING NET-ZERO EMISSIONS

The global transition to net-zero GHG emissions targets faces major economic obstacles and technological barriers and social challenges and political obstacles, despite increased political dedication and advancements in technology. The various obstacles that exist in different sectors and regions of the world combine to slow down climate change solutions while increasing the possibility of failing to meet net-zero emission deadlines.

Economic and Financial Barriers

The primary barrier to large-scale decarbonization efforts remains economic constraints. The combination of climate policy uncertainty and fluctuating regulatory systems together with ongoing fossil fuel support programs results in weaker investment signals that prevent capital from reaching low-

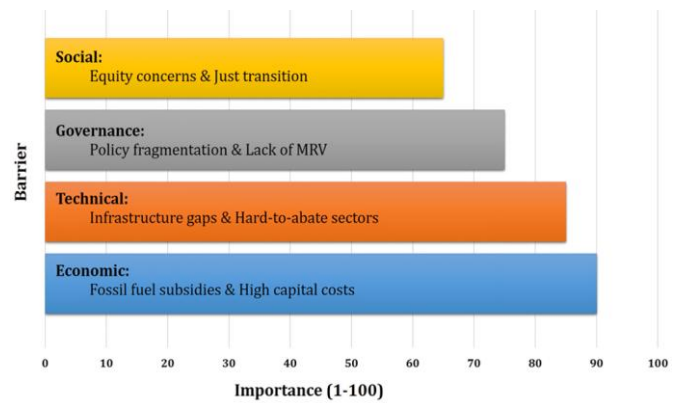


Figure 5. Conceptual framework of systemic barriers hindering the transition to net-zero emissions, categorized by economic, technical, governance, and social dimensions (OECD, 2024)

carbon technologies. Investors face challenges with climate solutions because they experience poor risk-return profiles in emerging and developing markets which suffer from financing shortages and high capital costs. The world continues to underinvest in clean energy and sustainable infrastructure and climate-smart agriculture because investors fail to recognize the long-term economic advantages of early climate action (Investor Group on Climate Change [IGCC], 2025; OECD, 2024). The transition is not merely a technical challenge but a multi-dimensional one. **Figure 5** categorizes primary hurdles, showing that economic constraints like fossil fuel subsidies, and governance issues, like policy fragmentation, act as the most critical bottlenecks to large-scale climate action.

Technological and Infrastructure Constraints

Technological barriers exist because organizations lack access to low-carbon technologies that organizations both need and require which those technologies did not yet achieve full development. The renewable energy sector achieved rapid development yet the sector still faces major problems in its hard-to-abate areas which include heavy industry and long-distance transport and agricultural operations. The current infrastructure problems result from insufficient electricity grids and energy storage systems and hydrogen supply chains and CCS networks which creates implementation difficulties for these technologies. The current pattern of technological diffusion leads to regional disparities which worsen the worldwide differences in mitigation capacity according to IPCC (2022).

Policy and Governance Challenges

Effective climate action depends on coherent and stable governance frameworks. The combination of fragmented policy frameworks and short political terms and limited institutional capacity hinders effective implementation of climate change initiatives. The climate objectives in numerous regions face inadequate sectoral integration which results in inefficient use of resources and misaligned policy development. International coordination problems together with different countries implementing their agreements at different levels of commitment create obstacles that hinder international progress. To expedite net-zero transitions

multilevel governance needs strengthening plus policy coherence needs enhancement and existing accountability enforcement systems must receive improvement (Hale et al., 2021; UNFCCC, 2023).

Social, Behavioral, and Equity Considerations

The ability to achieve net-zero pathways depends on social and political factors which determine their actual implementation. The public needs to accept climate policies and people must change their behavior while they should trust institutions to achieve long-term climate mitigation goals. Climate action faces delays and stoppages because special interests resist progress and people worry about losing jobs and how different groups will face economic impacts especially in cases where transition costs seem unfairly distributed. The international community has reached a growing consensus that a just transition needs to protect jobs while it creates social opportunities and reduces social gaps between and within countries to produce sustainable climate solutions (IPCC, 2022; Newell & Mulvaney, 2013).

Knowledge Gaps and Coordination Failures

The process of achieving net-zero targets encounters additional challenges because there are ongoing knowledge deficits that need to be resolved. The research faces three major challenges because there is not enough sector- and region-specific transition risk data and climate models fail to properly incorporate all economic and technological and social factors and the research lacks proof of effective governance and stakeholder partnership models. The successful implementation of climate solutions becomes more difficult because governments and private businesses and financial institutions and civil society fail to work together.

The research gaps can be resolved through better interdisciplinary research and increased data availability and improved collaboration between different sectors and governance levels (Falana et al., 2025). The research results demonstrate that to solve these ongoing systemic problems, organizations need to implement complete solutions which require them to maintain policy consistency, use specific financial tools, develop new technologies, practice inclusive governance, and involve citizens in decision-making. The interconnected problems must first be resolved before organizations can achieve their net-zero targets which currently exist as only future plans.

RESEARCH GAPS AND FUTURE DIRECTIONS

Scientists have made considerable advancements in climate science and policy development and technology progress yet research gaps continue to exist which hinder the successful implementation of net-zero GHG emission pathways. The global climate action strategies require these gaps to be addressed so their core elements of robustness and feasibility and equity can be improved.

Integration of Policy, Technology, and Socioeconomic Dimensions

The current research suffers from a critical flaw because it fails to integrate technological, economic, policy, and behavioral dimensions throughout its net-zero research. The majority of research studies individual sectors or technologies in isolation without considering the system-wide interactions and rebound effects and distributional impacts. Future research should adopt interdisciplinary and systems-based approaches that link emissions mitigation technologies with policy instruments market dynamics and social behavior patterns to enable better understanding of real-world complexities and development of effective climate strategies.

Sector- and Region-Specific Evidence Gaps

Current net-zero pathways use global and aggregated models to create their pathways which fail to depict regional differences and specific limitations of different sectors. The absence of detailed emissions data together with mitigation cost information and transition risk data makes it difficult to assess different geographical areas especially in developing and emerging economies. Regional modeling requires improvement along with the development of local studies to create context-based policies which direct investment decisions based on national development goals.

Uncertainty in Carbon Removal and Nature-Based Options

The net-zero scenarios now include CDR and nature-based options, yet their actual implementation remains uncertain because people do not know how these options will scale and persist and affect the environment and how they will get governed. Research needs to assess how well soil carbon sequestration and afforestation and new technological CDR methods will function in different climatic and socioeconomic situations. The MRV systems must improve because they serve as vital elements which help establish trust in the methods while stopping people from depending on doubtful offset options.

Data, Monitoring, and Accountability Challenges

The assessment of net-zero emissions progress needs two essential elements which are reliable data and transparent monitoring systems. The different sectors and regions face ongoing challenges because of two main problems which include inconsistent emissions accounting methods and difficulties in obtaining high-quality data. Future research should focus on developing standard measurement systems together with digital monitoring systems and public data sharing networks which will improve both national and corporate and sector-based transparency and accountability.

Governance, Stakeholder Engagement, and Just Transition

The success of net-zero strategies relies on their technical viability and their ability to be managed through effective governance systems and their capacity to gain public support. The research community needs to study governance systems which enable different government levels and various private sector and civil society organizations and local communities to

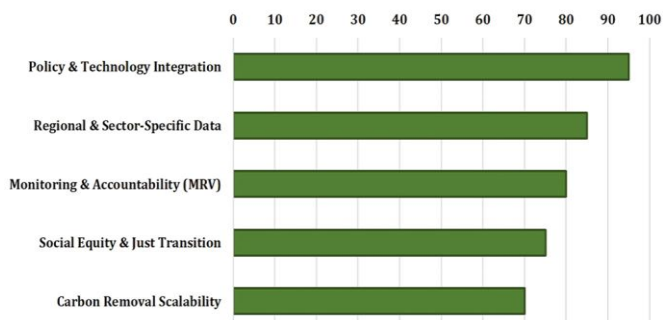


Figure 6. Priority ranking of identified research gaps for advancing global net-zero implementation (OECD, 2024)

work together. Empirical research which studies how to achieve a just transition through equity distribution and employment effects and social inclusion mechanisms has shown insufficient progress and needs dedicated research to improve understanding.

Emerging Priorities for Future Research

Future studies need to investigate how climate mitigation and adaptation efforts interact with sustainable development goals which include food security and biodiversity preservation and public health. AI and digital technology and integrated assessment modeling have created new possibilities which improve scenario analysis and risk assessment and policy evaluation. International research partnerships need to be strengthened through capacity-building programs to create evidence-based decision-making systems which help countries achieve their net-zero emissions targets. The research gaps need to be resolved because they establish the foundation for developing climate action pathways which will be scientifically valid and inclusive and operationally successful. Future research needs to focus on three core areas which include interdisciplinary research and data quality enhancement and strengthened governance and equity assessment to make a vital contribution toward achieving global net-zero GHG emission targets. As depicted in **Figure 6**, the integration of policy frameworks with technological innovation emerges as the highest priority for future research. This is followed by the need for granular, region-specific data, which is currently lacking in global models. Addressing these gaps is essential for moving from theoretical net-zero pledges to operational execution.

POLICY IMPLICATIONS AND RECOMMENDATIONS

The following policy recommendations are proposed to support the transition toward net-zero emissions:

- **Strengthening long-term policy certainty:** Establishing clear, stable, and legally binding climate targets to reduce investment risks and support long-term planning.
- **Scaling up climate finance:** Expanding public and private investment in low-carbon technologies, particularly in developing and emerging economies.

- **Enhancing MRV systems:** Improving transparency through standardized emissions accounting and digital monitoring technologies.
- **Promoting sector-specific transition strategies:** Designing tailored policies for key sectors such as energy, transportation, industry, and agriculture.
- **Supporting a just transition:** Implementing policies that address social equity, workforce reskilling, and regional economic diversification.
- **Strengthening international cooperation:** Enhancing coordination across countries through mechanisms such as the Global Stock take and technology transfer initiatives.

The achievement of net-zero targets requires stable and inclusive policy frameworks which enable organizations to measure their climate commitments through specific results. The review identifies key policy elements which must be implemented to achieve net-zero GHG emission targets across all sectors and regions (UNFCCC, 2015, 2023). The first step to create substantial investments in low-carbon technology and infrastructure requires stronger policy stability together with extended time period signals. The combination of legally binding climate targets with transparent implementation roadmaps and predictable carbon pricing together with long-term renewable energy goals and fossil fuel subsidy elimination schedule, creates essential conditions, which enable private sector participation while reducing investment risk (Fankhauser et al., 2022). Climate policies need to be combined with existing economic and development frameworks. The political viability of net-zero paths improves when they connect with job development and energy security and food security and innovation and industrial growth. The policies which support green industrial transformation and workforce reskilling and regional economic diversification will help decarbonization achieve its goal of creating sustainable development that benefits all people (OECD, 2024). The third main obstacle in climate finance development stands as the most significant barrier. Achieving net-zero emissions requires substantial increases in public and private investment across energy, transport, industry, agriculture, and the built environment. The investment gaps require development through public funding and risk-sharing instruments and better financial access for developing and emerging economies and international technology transfer and capacity building efforts. Fourth, effective climate commitment implementation requires operational systems that help measure GHG reductions through their function. The establishment of monitoring systems with reporting capabilities and verification processes, together with standardized emissions accounting methods and climate financial reporting integration into regulatory frameworks, will enhance accountability while supporting net-zero control in financial markets. International organizations use Global Stocktake mechanisms to help countries learn from their experiences while establishing higher climate change prevention goals (Newell & Mulvaney, 2013). Net-zero strategies need specific policies for each sector which match their particular context and which require people to commit to an equitable transition process. Energy industry transport building and agricultural sectors need customized policies which include specific CH₄

reduction incentives and climate-smart development programs to achieve quick environmental benefits without harming job security. Climate policy needs equity principles social dialogue systems and participatory governance methods to achieve permanent net-zero results which society will accept as acceptable (Hale et al., 2022).

CONCLUSION

The global community faces its most urgent and complex challenge through its quest to achieve net-zero GHG emissions. The review uses scientific evidence together with policy frameworks and technological pathways and sectoral insights to evaluate global progress toward net-zero emissions targets. Current global efforts remain insufficient to meet the Paris Agreement targets, primarily due to a persistent implementation gap—where existing policies and commitments are not effectively translated into measurable emissions reductions although ambition gaps in national climate targets (NDCs) also continue to play a significant role. The world has made progress in climate ambition and low-carbon technology deployment yet these efforts do not meet the Paris Agreement goals for global emissions reduction.

The transition to net-zero emissions demands urgent and fundamental transformations for all key sectors which encompass energy and transport and industrial operations and building systems and agricultural practices. The mitigation measures need to focus on achieving substantial emission reductions through direct measures while maintaining trustworthy carbon removal solutions to handle remaining emissions. The agricultural sector and livestock production serve as major emission sources yet they also function as essential elements for emission reduction because climate-smart practices and technological advancements and nature-based solutions create significant potential which depends on effective policy implementation.

Achieving net-zero emissions represents one of the most urgent and complex challenges facing the global community. While significant progress has been made in advancing climate ambition and deploying low-carbon technologies, current efforts remain insufficient to meet the Paris Agreement targets. Addressing this gap requires not only technological innovation but also stronger governance frameworks, sustained policy commitment, and enhanced financial support.

A successful transition to net-zero depends on integrated, cross-sectoral strategies that combine mitigation, adaptation, and sustainable development objectives. It also requires a just transition that ensures social equity, protects vulnerable communities, and supports workforce transformation.

Moving forward, the emphasis must shift from pledges to implementation. This includes translating climate commitments into measurable outcomes, strengthening monitoring systems, and accelerating coordinated global action. Only through sustained and collective efforts can net-zero pathways become both achievable and effective in limiting long-term climate risks.

Author contributions: **HK:** writing – original draft; **MR:** revising the manuscript; **BR, ZSY, & RNH:** writing – original draft, investigation, data curation, visualization; **HA & HGF:** writing – review & editing. All authors agreed with the results and conclusions

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that the study does not require approval from ethics committee. It is a review of existing literature.

AI statement: The authors stated that no AI tools were used during the study.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

REFERENCES

- Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, 29(3), 42539-42559. <https://doi.org/10.1007/s11356-021-18230-6>
- Bebber, D. P., Ramotowski, M. A. T., & Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, 3(11), 985-988. <https://doi.org/10.1038/nclimate1990>
- Dablander, F., Sachisthal, M. S. M., & Haslbeck, J. M. B. (2024). Climate actions by climate and non-climate researchers. *npj Climate Action*, 3, Article 105. <https://doi.org/10.1038/s44168-024-00187-1>
- Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., & Rosamond, L. (2018). Increase in crop losses to insect pests in a warming climate. *Science*, 361(6405), 916-919. <https://doi.org/10.1126/science.aat3466>
- Falana, J., Osei-Kyei, R., & Tam, V.W.Y. (2025). Critical barriers and success strategies to stakeholder partnership towards achieving net zero emissions building: A systematic literature review. *Cities*, 163, Article 106061. <https://doi.org/10.1016/j.cities.2025.106061>
- Fankhauser, S. (2022). The meaning and credibility of net-zero pledges. *Nature Climate Change*, 12(6), 491-493.
- Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., & Wetzer, T. (2021). The meaning of net zero and how to get it right. *Nature Climate Change*, 12(1), 15-21. <https://doi.org/10.1038/s41558-021-01245-w>
- Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R. ... Zeng, J. (2025). Global carbon budget 2024. *Earth System Science Data*, 17, 965-1039. <https://doi.org/10.5194/essd-17-965-2025>

- Hale, T., Kuramochi, T., Lang, J., Smith, S. M., Black, R., & Füssler, J. (2021). Credibility of net-zero emissions targets. *Climate Policy*, 22(1), 18-29. <https://doi.org/10.1080/14693062.2021.2013155>
- Hale, T., Setzer, J., & Byrne, R. (2022). Delivering net zero: A framework for credibility. *Energy Research & Social Science*, 91, Article 102724. <https://doi.org/10.1016/j.erss.2022.102724>
- IEA. (2023). Net zero roadmap: A global pathway to keep the 1.5 °C goal in reach. *International Energy Agency*. <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>
- IGCC. (2025). Global investment gaps in climate mitigation and adaptation. *Investor Group on Climate Change*. <https://www.unep.org/resources/adaptation-gap-report-2025>
- IMF. (2022). World economic outlook: Climate change and macro-financial risks. *International Monetary Fund*. <https://www.imf.org/en/publications/weo>
- IPCC. (2013). *Climate change 2013: The physical science basis*. Cambridge University Press.
- IPCC. (2022). *AR6 working group III: Mitigation of climate change*. Cambridge University Press.
- IPCC. (2023). *AR6 Synthesis report: Climate change 2023*. Cambridge University Press.
- Kioumars, H., Naseri Harsini, R., Özbey, B. G., Rafiei, B., Alidoust Pahmedani, M., Yahaya, Z. S., & Rosen, M. A. (2026). Wildlife, biodiversity, and the United Nations sustainable development goals: Synergizing conservation and development for a sustainable future. *European Journal of Sustainable Development Research*, 10(2), Article em0367. <https://doi.org/10.29333/ejosdr/17816>
- Mahdavian, S. M., Askari, F., Kioumars, H., Naseri Harsini, R., Dehghanzadeh, H., & Saboori, B. (2024). Modeling the linkage between climate change, CH4 emissions, and land use with Iran's livestock production: A food security perspective. *Natural Resources Forum*, 49(3), 2954-2977. <https://doi.org/10.1111/1477-8947.12532>
- Newell, P., & Mulvaney, D. (2013). The political economy of the 'just transition'. *The Geographical Journal*, 179(2), 132-140. <https://doi.org/10.1111/geoj.12008>
- OECD. (2023). Climate action and economic growth. *Organisation for Economic Co-operation and Development*. https://www.oecd.org/en/publications/2023/11/the-climate-action-monitor-2023_d9ee6e77.html
- OECD. (2024). Financing climate transitions and net-zero pathways. *Organisation for Economic Co-operation and Development*. <https://www.oecd.org/en/topics/climate-mitigation-and-net-zero-transition.html>
- Rafiei, B. (2025). Climate change impacts on pest and beneficial insects: Challenges and management strategies for adaptation. *Arthropods*, 14(3), 82-93.
- Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., & Vilariño, M. V. (2018). Mitigation pathways compatible with 1.5 °C. In *Global warming of 1.5 °C* (pp. 93-174). Cambridge University Press.
- Rosen, A. R., Kioumars, H., & Gholipour Fereidouni, H. (2025). Climate action and net-zero emissions. *European Journal of Sustainable Development Research*, 9(4), Article em0334. <https://doi.org/10.29333/ejosdr/16864>
- SBTi. (2023). Corporate net-zero standard. *Science Based Targets Initiative*. <https://sciencebasedtargets.org/net-zero>
- Smith, L. G., Kirk, G. J. D., Jones, P. J., & Williams, A. G. (2024). The greenhouse gas impacts of livestock systems. *Global Change Biology*, 30(4), Article e16984.
- Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., & Tubiello, F. (2023). Agriculture, forestry and other land use (AFOLU). *Nature Climate Change*, 13(2), 123-135.
- Stern, N. (2006). *The economics of climate change: The Stern review*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511817434>
- UN. (2021). Net zero coalition: Global roadmap. *United Nations*. <https://www.un.org/en/climatechange/net-zero-coalition>
- UNEP. (2023). Emissions gap report 2023. *United Nations Environment Program*. <https://www.unep.org/resources/emissions-gap-report-2023>
- UNFCCC. (2015). Paris agreement. *United Nations Framework Convention on Climate Change*. <https://unfccc.int/process-and-meetings/the-paris-agreement>
- UNFCCC. (2023). Global stocktake synthesis report. *United Nations Framework Convention on Climate Change*. <https://unfccc.int/global-stocktake-secretariat-synthesis-reports-and-addendas>
- WMO. (2025). WMO confirms 2024 as warmest year on record at about 1.55 °C above pre-industrial level. *World Meteorological Organization*. <https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level>
- World Economic Forum, FAO, & CGIAR. (2025). Nature-based solutions for climate mitigation in agriculture. *World Economic Forum*. https://wwfe.awsassets.panda.org/downloads/2023_wwf_report_nbs.pdf