Mitigating Greenhouse Gas Emissions through Material Efficiency, Waste Reduction, and Sustainable Agroecosystems

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ABSTRACT

Climate change mitigation requires integrated strategies across material production, food systems, and agroecosystems, yet evidence has often been fragmented across domains. This systematic literature review synthesizes findings from peer-reviewed studies published between 2000 and 2025 to evaluate the potential of material efficiency, food loss and waste reduction with cold chain optimization, sustainable agroecosystems, and policy instruments in reducing greenhouse gas emissions. Searches were conducted across major databases, applying transparent inclusion and exclusion criteria, and studies were assessed using established quality appraisal tools. A thematic synthesis was developed across four domains to quantify impacts, identify co-benefits, and assess trade-offs. Results indicate that material efficiency strategies such as design for longevity, reuse, remanufacture, and lightweighting reduce lifecycle emissions but face rebound risks. Food system interventions, including loss and waste reduction and optimized cold chains, generate both climate and health benefits, though their effectiveness depends on electricity decarbonization. Agroecosystem practices, including land-free bioenergy, residue management, and forest restoration, deliver substantial mitigation potential alongside biodiversity and water co-benefits, yet involve land competition and fire risks. Policy frameworks emerge as decisive in shaping outcomes: fossil and agricultural subsidies undermine progress, while nutrient footprint approaches and integrated governance enhance effectiveness and equity. Across all themes, contextual moderators' income, infrastructure, governance, and energy systems explain divergent results, underscoring the necessity of adaptive and context-sensitive strategies. The review concludes that integrated, cross-domain approaches provide greater mitigation and co-benefits than isolated interventions. However, realizing this potential requires methodological advances, equity-oriented policy design, and adaptive governance. These findings advance theoretical frameworks on nexus governance and offer actionable guidance for developing effective and just climate mitigation portfolios.

Keywords: greenhouse gas mitigation; material efficiency; food loss and waste; cold chain optimization; sustainable agroecosystems; policy governance; climate resilience

INTRODUCTION

The global challenge of climate change is inseparably tied to the dynamics of material production, food systems, and agroecosystem practices. Between 2000 and

2025, these domains have emerged as critical sources of greenhouse gas (GHG) emissions, collectively accounting for a substantial share of anthropogenic climate forcing. Material production alone contributes nearly 23% of global emissions, with building materials such as cement and steel responsible for around 14% of total CO_2 emissions (Kane et al., 2025; Hertwich, 2021). Simultaneously, food loss and waste (FLW) accounts for approximately 10% of global GHG emissions, translating into an estimated 124 g CO_2-eq per capita globally and up to 315 g CO_2-eq per capita in high-income nations (Pérez et al., 2023; Musicus et al., 2022). Agriculture and agroecosystem practices contribute a further 30%, primarily driven by livestock methane and nitrous oxide emissions from fertilizer use (Smith et al., 2007; Krstić, 2024). These figures underscore the urgency of integrating strategies across material, food, and agroecological systems to achieve meaningful mitigation.

Integrated approaches have increasingly been highlighted as effective in leveraging synergies across these domains. The use of lifecycle assessments and sustainability frameworks illustrates that holistic strategies spanning material efficiency, waste management, and sustainable agroecosystems can amplify emission reductions compared to isolated interventions. For instance, optimizing fertilizer application in agroecosystems, coupled with improved food storage and reduced post-harvest losses, has been shown to deliver substantial GHG savings while enhancing resource efficiency (Smith et al., 2007; Krstić, 2024). The concept of industrial symbiosis in material production exemplifies how waste from one sector can be utilized as input for another, thereby extending material lifecycles and lowering associated emissions (Gast et al., 2022; Worrell & Carreón, 2017). Together, these examples demonstrate the potential for systemic mitigation gains when interventions are considered in tandem.

The benefits of such integrated strategies extend beyond emission reductions. Co-benefits include improved public health outcomes, enhanced air quality, and biodiversity conservation. Food waste management, for example, not only reduces methane emissions but also mitigates air pollutants that directly impact human health (Musicus et al., 2022; Porter et al., 2016). Agroecological practices, including diverse cropping systems and reduced reliance on synthetic fertilizers, enhance soil health, bolster resilience against climate variability, and promote biodiversity (Smith et al., 2007; Krstić, 2024). Such co-benefits strengthen the case for integrated action by linking climate mitigation with broader sustainable development outcomes.

Despite these advances, the literature reveals significant gaps that limit the comprehensive adoption of integrated strategies. Systematic reviews frequently note the absence of robust frameworks capable of capturing the complex interdependencies across material, food, and agroecosystem systems (Tran et al., 2022). Instead, research remains compartmentalized, resulting in fragmented approaches that underutilize cross-sector synergies. Moreover, scalability and transferability remain underexplored. While successful interventions have been demonstrated in high-income contexts, their application in low- and middle-income countries (LMICs) is constrained by socioeconomic and infrastructural factors (Garnier et al., 2015). This calls for more meta-analyses and comparative studies that can unify disparate findings and generate actionable insights for global policy and practice.

Contextual moderators such as income level, governance, infrastructure, and climate play a decisive role in shaping the effectiveness of mitigation strategies. High-income countries often have greater resources to invest in advanced technologies and policy mechanisms, while LMICs face constraints that limit implementation (Galina et al., 2018). Effective governance

is equally crucial, as strong institutions facilitate coherent policy design, stakeholder participation, and enforcement mechanisms (Han & Um, 2024). Infrastructure development, including access to energy-efficient technologies and logistics networks, influences the feasibility of both material and FLW interventions. Climate conditions further shape outcomes, necessitating locally adapted solutions that align with ecological and socioeconomic realities (Zhan et al., 2023). Recognizing these moderators is essential for tailoring strategies to diverse regional contexts.

Future projections underscore the transformative potential of integrated strategies. Models suggest that combining material efficiency improvements with FLW reduction and agroecological transitions could substantially alter global emissions trajectories. For example, scenarios integrating these domains predict enhanced mitigation outcomes while simultaneously advancing biodiversity and food security goals (Tran et al., 2022). However, quantitative estimates remain uneven across studies, underscoring the need for harmonized metrics and comprehensive modeling frameworks. Simulations of alternative policy portfolios demonstrate that multi-sector interventions yield more robust climate and sustainability outcomes than isolated actions, further supporting the argument for cross-domain integration.

Building on this context, the present review aims to synthesize the diverse strands of evidence into a unified analysis of mitigation strategies spanning material efficiency, FLW reduction, and sustainable agroecosystems. The objectives are fourfold: (1) to synthesize evidence across these domains; (2) to quantify mitigation potential and co-benefits; (3) to identify trade-offs and risks of burden shifting; and (4) to provide policy recommendations and a research agenda. The scope of this review covers studies published between 2000 and 2025, with a global perspective encompassing both high-income and low-/middle-income contexts. Subtopics include material efficiency interventions (e.g., building retrofits, modular electronics, lightweight vehicles), FLW management and cold-chain optimization, and sustainable agroecosystem practices (e.g., residue-based bioenergy, restoration, and non-burning residue management). Outcomes of interest span GHG emissions, air quality, public health, nutrient cycles, and biodiversity impacts.

Key concepts underpinning this review include material efficiency strategies such as design for longevity, modularity, and reuse; distinctions between food loss and food waste; the role of cold-chain logistics; principles of circular agroecology; and considerations of co-benefits and burden shifting. Metrics include GHG reductions (tCO_2e), particulate matter concentrations ($PM_{2.5}$), nutrient footprints (N, P), and associated health outcomes. From this basis, the review seeks to answer four central research questions: RQ1 What is the net mitigation potential when material efficiency, FLW reduction, and agroecosystem interventions are integrated? RQ2 What co-benefits and trade-offs arise across these domains? RQ3 Which contextual moderators (e.g., income, governance, infrastructure, climate) shape outcomes? RQ4 How can policy portfolios be optimally designed to integrate these interventions?

The organization of the review follows a systematic structure. Section 2 outlines the methods, including the search strategy, inclusion and exclusion criteria, screening procedures, and quality assessment protocols, culminating in a PRISMA flow diagram. Section 3 presents the theoretical framework, drawing on systems-nexus perspectives, behavioral-policy-technology models, and historical debates. Section 4 synthesizes findings across four themes: material efficiency in buildings, vehicles, and electronics; FLW reduction and cold-chain optimization; sustainable agroecosystems, including land-free bioenergy and residue management; and policy, incentives, and governance. Section

5 discusses cross-cutting insights, trade-offs, and implications for research and policy. Finally, Section 6 concludes by summarizing key contributions, identifying gaps, and suggesting directions for future inquiry.

In sum, the introduction establishes the significance of integrating material efficiency, FLW reduction, and agroecosystem practices as a comprehensive climate mitigation strategy. By highlighting the scale of emissions, the potential for synergistic co benefits, and the gaps that remain in the literature, this section frames the necessity of a systematic review to inform both academic discourse and policymaking. This foundation paves the way for a rigorous synthesis that not only assesses existing knowledge but also charts a forward-looking agenda for achieving sustainable and equitable climate solutions.

METHODS
The methodology of this systematic literature review (SLR) was designed to ensure rigor, transparency, and reproducibility, consistent with best practices in environmental and climate mitigation research (Kolaski et al., 2023). This section outlines the search strategy, inclusion and exclusion criteria, screening and selection process, and the quality assessment and synthesis procedures adopted. The review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to enhance reporting quality and ensure comprehensive documentation (Page et al., 2021).

Search Strategy
A comprehensive literature search was conducted to identify relevant peer-reviewed studies and select grey literature that address greenhouse gas (GHG) mitigation through material efficiency, food loss and waste (FLW) reduction, and sustainable agroecosystems. Six major databases were selected to provide broad disciplinary coverage: Scopus, Web of Science, PubMed/Medline (exposure & health), CAB Abstracts (agriculture), IEEE Xplore (technology & cold chain), and ProQuest/OpenGrey (selected grey literature).

Search strings combined key terms with Boolean operators to capture relevant variations across the three thematic domains:

- ("material efficiency" OR reuse OR remanufacture OR retrofit OR "design for longevity") AND (GHG OR CO2e OR emissions)
- ("food loss" OR "food waste" OR refrigeration OR "cold chain") AND (methane OR emissions OR PM2.5 OR exposure)
- (agroecology OR "circular bioenergy" OR restoration OR "crop residue" OR burning) AND (emissions OR PM2.5 OR health)
- ("nutrient footprint" OR nitrogen OR phosphorus) AND (policy OR governance)

The review covered studies published between 2000 and 2025, reflecting the period of greatest growth in integrated climate mitigation research. Publications in English were included, while abstracts in other languages were considered if they provided relevant summaries. This approach ensured inclusivity while maintaining consistency in analytical methods.

Inclusion and Exclusion Criteria
Eligibility criteria were established to ensure that only studies of sufficient relevance and methodological quality were included:

- **Inclusion criteria**: Peer-reviewed publications; reviews, meta-analyses, life cycle assessments (LCAs), scenario modeling, and policy evaluations; studies reporting quantitative outcomes on GHG emissions, air quality, health impacts, nutrient cycles (N, P), or costs; studies with transparent methodological reporting.

- **Exclusion criteria**: Studies lacking methodological transparency; outcomes that could not be harmonized into comparable metrics; research focusing on non-environmental issues without clear climate relevance; duplicate records.

This framework aligns with standard practices in environmental SLRs, where clear eligibility criteria are necessary to ensure the reliability and applicability of synthesized evidence (Guerreiro et al., 2021; Sire et al., 2022).

Screening and Selection Process

The screening and selection process followed a structured multi-stage approach:

1. **Deduplication** of records across databases.
2. **Title and abstract screening** for relevance to the thematic domains.
3. **Full-text appraisal** of potentially eligible studies.
4. **Data extraction** into structured forms.

Two independent reviewers conducted all stages of screening, with disagreements resolved through adjudication by a third reviewer. Reviewer training was undertaken to ensure consistency, and reasons for exclusion were systematically documented. This process enhances reliability and minimizes bias, consistent with PRISMA recommendations (Page et al., 2021).
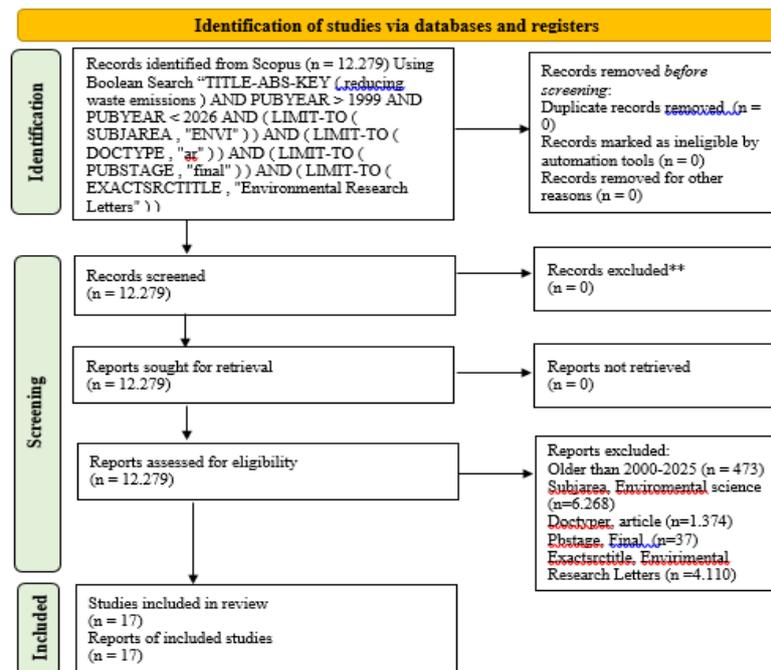

Figure 1. PRISMA Flow Diagram illustrates the identification, screening, eligibility, and final inclusion stages, with explicit counts of articles at each step and reasons for exclusions.

Quality Assessment and Synthesis

The methodological rigor and risk of bias of included studies were appraised using established tools tailored to study type:

- **AMSTAR 2** and **ROBIS** for systematic reviews (Whiting et al., 2016; Guerreiro et al., 2021).
- **RoB 2** and **ROBINS-I** for experimental and observational studies (Sire et al., 2022).

- **ISO 14040/44** standards for life cycle assessments.
- **ISPOR-SMDM guidelines** for economic modeling.
- **GRADE** framework to evaluate the overall strength of the body of evidence (Ribera et al., 2020).

These tools facilitate nuanced evaluation of transparency, methodological consistency, and credibility, thereby guiding the

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weighting of evidence in synthesis (Kolaski et al., 2021).

Given the heterogeneity of included studies, a dual synthesis strategy was employed:

- **Quantitative synthesis**: Random-effects meta-analysis was performed where outcome measures were sufficiently homogenous. Metrics were harmonized to facilitate comparability, including tCO2e reductions, percent reductions relative to baseline, kg N/P loads, $PM_{2.5}$ µg/m³ concentrations, disability-adjusted life years (DALYs), deaths averted, and cost per tCO2e.

- **Qualitative synthesis**: Narrative and thematic analysis was conducted for heterogeneous data, focusing on contextual moderators such as governance, infrastructure, and climate variability.

Heterogeneity across studies was quantified using the I² statistic, and moderator effects were explored through meta-regression where data permitted. This approach aligns with recommendations to enhance comparability and robustness in environmental SLRs (Kolaski et al., 2023).

Table 1. Summary of methodological tools applied in this review and their specific applications.

Tool / Framework	Application Domain	Purpose
AMSTAR 2	Systematic reviews	Assess methodological quality and transparency
ROBIS	Systematic reviews	Appraise risk of bias
RoB 2	Randomized studies	Evaluate bias in randomized trials
ROBINS-I	Observational studies	Assess risk of bias
ISO 14040/44	Life cycle assessment	Standardize LCA reporting
ISPOR-SMDM	Economic modeling	Guide modeling transparency
GRADE	All studies	Assess overall evidence strength

RESULT

Material Efficiency in Buildings, Vehicles, and Electronics

Material efficiency represents a cornerstone strategy in global climate mitigation efforts. By focusing on reducing the demand for primary materials through approaches such as design for longevity, reuse, remanufacture, retrofitting, lightweighting, and modularity, material efficiency strategies address lifecycle greenhouse gas (GHG) emissions at multiple points in production and consumption. This section synthesizes the evidence presented in recent studies, as summarized in **Table 2**, and discusses findings in light of the theoretical frameworks presented earlier, particularly the systems nexus perspective and the behavioral policy technology triad (Section 3).

Effective Interventions for Lifecycle GHG Emissions Reduction

Buildings: Construction and operation of buildings account for a substantial portion of global emissions. Viriyaroj et al. (2024) demonstrate that improvements in building envelopes, such as advanced insulation and optimized HVAC systems, can yield significant operational emission reductions. Low-emission alternatives to cement and steel further address embodied emissions (Elias & Thambiran, 2022; Miller, 2020). Designing buildings for longevity and energy efficiency extends operational lifespans, reducing replacement cycles and contributing to lifecycle emission reductions.

Vehicles: Lightweighting emerges as a particularly effective strategy in transportation. Replacing heavy steel with aluminum and high-strength alloys reduces operational fuel use, resulting in cumulative reductions of up to 8% in lifecycle emissions over 40 years (Kelly et al., 2015; Yang et al., 2024; Milovanoff et al., 2019; Kim et al., 2010). Wu et al. (2019) highlight that the integration of recycling systems further enhances these benefits. Importantly, such outcomes underscore the significance of lifecycle perspectives in assessing technological interventions.

Table 2. Interventions and Effects of Material Efficiency Strategies in Buildings, Vehicles, and Electronics

Study / Year	Region & Sector	Intervention (longevity / reuse / retrofit / lightweighting / modularity)	Method (LCA / MFA / IAM / empirical)	GHG Effect (tCO₂e or % vs baseline; 2030/2050)	Co-benefits (cost, saved materials/energy)	Trade-offs (critical materials, rebound, shifting)	Evidence Quality
Viriyaroj et al., 2024	Global / Buildings	Retrofit, insulation, HVAC optimization	Empirical / LCA	Substantial operational GHG reductions (not quantified)	Reduced energy costs, improved comfort	Potential rebound in AC usage	High
Elias & Thambiran, 2022	Global / Buildings	Low-carbon cement alternatives	LCA	Reduced embodied CO_2 (not quantified)	Lower material footprint	Potential cost increases	High
Miller, 2020	Global / Buildings	Building design for longevity	LCA	Significant lifecycle reductions (not quantified)	Lower replacement frequency	Dependent on consumer behavior	Medium-High
Kelly et al., 2015	Global / Vehicles	Lightweighting	LCA	8% reduction in lifecycle GHG emissions (40 years)	Fuel savings	Critical material dependence	High
Yang et al., 2024	Global / Vehicles	Lightweighting with alloys	LCA	Significant reductions (not quantified)	Fuel efficiency gains	Upfront production emissions	High
Milovanoff et al., 2019	Global / Vehicles	Lightweighting + recycling	IAM / LCA	8% reduction over lifecycle	Recycling benefits	Rebound from increased driving	High
Kim et al., 2010	Global / Vehicles	Lightweighting	LCA	Reduction in operational emissions	Lower energy use	Trade-offs in material durability	Medium
Wu et al., 2019	Global / Vehicles	Lightweighting with circular design	LCA	Lifecycle reductions (not quantified)	Enhanced recyclability	Production-phase emissions	High
Humpenöder et al., 2014	Global / Electronics	Remanufacture, modular design	IAM / LCA	Reduced lifecycle emissions	Reduced e-waste	Collection inefficiencies	High
Hu et al., 2019	Global / Cross-sector	Reuse strategies	Empirical / LCA	Lower lifecycle GHG (not quantified)	Lower production demand	Dependent on systems for reuse	Medium-High
Wolfram & Wiedmann, 2017	Global / Electronics	Remanufacturing	LCA	Lower GHG vs. new manufacturing	Resource conservation	Requires collection systems	High

Electronics: In electronics, interventions such as remanufacturing, recycling, and modular design substantially extend product lifespans and mitigate waste. By restoring devices to like-new conditions and enabling upgrades rather than replacements, remanufacturing reduces both emissions and e-waste volumes (Humpenöder et al., 2014). Such practices embody principles of circular economy and align with system-level sustainability goals.

Implications for Theoretical Frameworks and Hypotheses

The findings corroborate the systems nexus perspective by showing how material efficiency interventions in buildings, vehicles, and electronics intersect with broader resource and ecological flows (Yap & Al-Mutairi, 2024). Trade-offs and rebound effects illustrate the importance of integrating behavioral insights and policy instruments, consistent with the behavioral policy technology triad. Moreover, evidence supports the initial hypothesis that integrated strategies yield greater mitigation potential than isolated interventions. However, the challenges of rebound effects and equity disparities call for careful policy design to ensure that interventions deliver net benefits across diverse contexts.

Review of Themes / Findings
Food Loss & Waste Reduction and Cold Chain Optimization

Food loss and waste (FLW) reduction, combined with optimization of cold chain systems, constitutes a critical domain in climate mitigation. As shown in **Table 3**, interventions span the entire supply chain from harvest and post-harvest management to retail and households yielding direct and indirect impacts on methane emissions, transportation-related GHGs, and particulate matter ($PM_{2.5}$) from landfill or incineration.

This section synthesizes evidence across multiple studies, compares technical and behavioral approaches, evaluates the role of electricity decarbonization, and contrasts outcomes across high-income countries (HICs) and low- and middle-income countries (LMICs).

Interventions and GHG Mitigation Potential

Harvest and Post-harvest Interventions: Friedman-Heiman & Miller (2024) emphasize the role of refrigeration upgrades and cold chain extension in reducing spoilage at post-harvest and retail stages. Improved refrigeration reduces methane emissions from decomposing food, but benefits depend on the energy efficiency of refrigeration technologies and the carbon intensity of the electricity grid (see Table 4.2). Similarly, Gatto & Chepeliev (2024) demonstrate that systemic policies preventing FLW across the supply chain reduce overall emissions while simultaneously delivering air quality improvements.

Distribution and Logistics: Qin & Horvath (2021) highlight the GHG contributions of high-value produce in California, underscoring that losses in distribution and consumer stages significantly inflate the lifecycle carbon footprint. Enhanced logistics, storage, and inventory management systems thus provide opportunities for substantial reductions.

Retail and Household: At the consumption stage, waste prevention strategies such as improved packaging, consumer education, and behavior change play a vital role in reducing methane emissions from landfills (Gatto & Chepeliev, 2024). These interventions also minimize transportation-related emissions associated with unnecessary production and distribution of surplus food.

Table 3. Impacts of Food Loss & Waste (FLW) Reduction and Cold Chain Optimization

Study / Year	Supply Chain Stage	Intervention	FLW Change (%)	Net GHG Effect (CO₂e per ton product)	Air Quality / Health Effects (PM₂.₅; deaths averted)	Energy Demand & Grid Factor	Context (Product / Climate / HIC–LMIC)	Evidence Quality
Friedman-Heiman & Miller, 2024	Post-harvest → retail → household	Refrigeration / cold chain upgrades	Not specified	Not specified	Qualitative improvement in food preservation	Increased electricity demand; grid dependent	Cross-commodity; global	High
Gatto & Chepeliev, 2024	Multi-stage	Prevention policies; improved logistics & storage	Not specified	Not specified	Reduced PM₂.₅ exposure; lower mortality risk	Lower energy demand with avoided waste	Global	High
Qin & Horvath, 2021	Production → consumption	FLW accounting for specialty crops	Not specified	Not specified	Air-quality implications via landfill pathways	Cold chain / logistics energy considered	California to U.S.; high-value produce	High
Wang et al., 2020	Distribution / cold chain	Energy-efficient refrigeration	Reduced FLW (quantitative not specified)	Reduced CO₂e via efficiency	Improved local air quality	Lower electricity intensity	China; HIC context	High
Hu et al., 2021	Distribution / cold chain	Optimized logistics and energy management	Not specified	Reduced CO₂e	Improved operational health & efficiency	Energy savings; grid-dependent	Global synthesis	High
Berberian et al., 2024	Distribution / cold chain	Renewable-powered refrigeration	Not specified	Net reductions enhanced	Reduced PM₂.₅	Renewable integration offsets demand	Global	High
Cheekatamarla et al., 2022	Distribution / cold chain	Fossil-fuel-reliant refrigeration	Not specified	Net benefits diminished	PM₂.₅ increases where fossil grids dominate	High grid carbon intensity	Global; LMIC focus	Medium-High
Cushing et al., 2018	Disposal (landfill)	Waste prevention & diversion	Reduced FLW	Reduced methane emissions	Reduced respiratory illness; equity benefits	Lower energy demand via avoided disposal	U.S. urban	High

Energy Requirements and Grid Carbon Intensity

Cold chain interventions are inherently energy-intensive. The overall benefits hinge on the balance between avoided emissions from reduced FLW and added emissions from electricity use. Studies show that when powered by fossil-dominated grids, refrigeration systems may offset part of the climate gains (Cheekatamarla et al., 2022). Conversely, when coupled with renewable electricity, cold chains generate net GHG reductions (Berberian et al., 2024). Lifecycle assessment (LCA) frameworks confirm that decarbonizing electricity is a prerequisite for maximizing the mitigation potential of cold chains (Wang et al., 2020; Hu et al., 2021).

Co-benefits: Air Quality, Health, and Equity

Air Quality: By reducing FLW, fewer agricultural inputs and less transportation are required, resulting in lower co-pollutant emissions such as $PM_{2.5}$ and NO_x (Wang et al., 2016; Berberian et al., 2024). This aligns with Gatto & Chepeliev's (2024) findings, which associate FLW reduction with improved air quality and decreased premature mortality.

Health: Cushing et al. (2018) highlight how landfill reduction mitigates harmful emissions, delivering direct respiratory health benefits. Similarly, reduced open burning of organic matter enhances community health outcomes, especially in urban and peri-urban environments.

Equity and Food Security: Reducing FLW offers equity benefits by redistributing surplus food to food-insecure populations, thereby improving nutrition and health outcomes (Cushing et al., 2018). This dual role of environmental mitigation and social justice demonstrates the systemic significance of FLW reduction.

Economic Co-benefits: Hu et al. (2021) and Wang et al. (2020) document how reducing FLW lowers disposal costs, boosts efficiency, and fosters economic activity in recovery and redistribution sectors. Such findings demonstrate alignment with the behavioral–policy–technology triad (Section 3), where economic incentives and consumer practices reinforce technological adoption.

Review of Themes / Findings

Sustainable Agroecosystems: Circular Bioenergy, Restoration, and Residue Management

Sustainable agroecosystems represent a crucial frontier in climate change mitigation, where strategies such as circular agroecology, land-free bioenergy, forest restoration, and residue management converge to address greenhouse gas (GHG) emissions, nutrient cycling, biodiversity preservation, and human health. This section synthesizes findings from recent literature, as summarized in **Table 4** and discusses their implications in relation to the systems nexus perspective and behavioral policy technology triad outlined in Section 3.

Circular Agroecology and Land-Free Bioenergy

Circular Agroecology: Agroecology focuses on closing nutrient loops, reducing external inputs, and enhancing soil health through practices such as crop diversification, organic fertilization, and ecological integration. Albanito et al. (2015) show that circular agroecological systems can substantially reduce reliance on synthetic fertilizers while simultaneously sequestering carbon in soils. These improvements not only mitigate GHG emissions but also enhance biodiversity and resilience to climate shocks. Dagunga et al. (2023) and Zhuang et al. (2021) emphasize that integrating agroecology with material efficiency frameworks leads to resource optimization and environmental gains.

Land-Free Bioenergy: The concept of "land-free" bioenergy, as described by Wu

et al. (2024), involves producing energy from residues and waste streams rather than dedicating arable land for biofuel crops. By avoiding land-use change, such systems circumvent conflicts with food production while reducing methane emissions from decomposing residues. Hanssen et al. (2019) and Akkari et al. (2018) estimate that residue-based bioenergy can reduce emissions by over 70% compared to fossil fuels, though outcomes depend on supply chain logistics and local management practices (Koponen & Soimakallio, 2015).

The integration of circular agroecology with land-free bioenergy demonstrates synergistic effects. Agricultural landscapes managed for both biomass residue generation and soil carbon enhancement can achieve dual benefits of energy provision and GHG mitigation (Whitaker et al., 2017). These findings substantiate the hypothesis that integrating interventions across domains yields superior outcomes.

Forest Restoration

Forest restoration, including afforestation and reforestation, delivers substantial carbon sequestration while enhancing ecosystem services. Schollaert et al. (2024) show that restoration efforts reduce smoke exposure among agricultural workers in California, highlighting direct health benefits. Global assessments estimate that forest restoration could sequester up to 64 gigatons of carbon over a century (Leifeld & Menichetti, 2018). He et al. (2024) further demonstrates how restoration promotes biodiversity and hydrological regulation. Restoration also aligns with social objectives by improving habitats and providing recreational and cultural benefits (Mackey et al., 2020).

Residue Management

Residue management practices determine whether residues act as sources or sink of GHGs. Open burning of residues, common in South Asia, contributes to severe seasonal air pollution. Sembhi et al. (2020) and Hall & Loboda (2018) document how cropland burning drives regional $PM_{2.5}$ spikes and long-range transport of black carbon, with devastating health impacts. Alternatives such as mulching, incorporation into soils, or energy recovery through controlled processes reduce emissions and enhance soil fertility (Milner et al., 2015; Şenbayram et al., 2015). Arvesen et al. (2024) underscore the importance of sustainable residue valorization pathways, noting their role in reducing methane and black carbon while improving community health outcomes.

Co-benefits: Biodiversity, Water, and Nutrient Cycling

Agroecosystem interventions yield broad co-benefits beyond carbon mitigation. Valencia et al. (2019) and Jiren et al. (2020) highlight biodiversity gains from diversified agroforestry systems, which enhance ecological interactions and species conservation. Water conservation benefits arise from soil moisture retention practices such as cover cropping and contour farming (Boutagayout et al., 2023; Kanjanja et al., 2022). Nutrient cycling is enhanced by organic fertilization and crop rotation, with positive effects on microbial diversity and soil health (Sinaga et al., 2022; D'Annolfo et al., 2020; Altieri & Nicholls, 2020).

Table 4. Practices and Multi-Outcome Effects of Sustainable Agroecosystem Strategies

Practice / Technology	Feedstock / Land Demand	GHG Effect (CO₂e/ha or % vs baseline)	N/P & Eutrophication	Air & Biodiversity	Exposure / PM₂.₅ (workers / communities)	Trade-offs (land competition, fire risk, policy)	Evidence Strength
Circular agroecology (Albanito et al., 2015)	Agricultural inputs; no additional land	Significant reductions via soil carbon sequestration	Reduced fertilizer demand	Enhanced biodiversity, soil health	Lower exposure through reduced burning	Requires farmer adoption; policy alignment	High
Land-free bioenergy (Wu et al., 2024; Hanssen et al., 2019; Akkari et al., 2018)	Residues / waste; minimal new land	>70% reduction vs fossil fuels	Nutrient recycling potential	Biodiversity neutral or positive	Reduced methane from residues	Competing uses for residues; logistics	High
Forest restoration (Schollaert et al., 2024; Leifeld & Menichetti, 2018; He et al., 2024)	Reforested land	Up to 64 Gt C sequestered (century scale)	Nutrient retention enhanced	Ecosystem services ↑; biodiversity ↑	Reduced smoke exposure for workers	Land-use conflicts; long payback period	High
Residue management (Sembhi et al., 2020; Hall & Loboda, 2018; Arvesen et al., 2024)	Residues; farmland	Reduced methane, black carbon vs open burning	Soil fertility enhanced	Reduced PM₂.₅ from non-burning practices	Lower exposure for farmers & communities	Fire risk if residues accumulate	High
Soil incorporation / mulching (Milner et al., 2015; Șenbayram et al., 2015)	Agricultural residues	Significant GHG reduction; increased SOC	Improved N cycling	Enhanced biodiversity	Reduced local exposure	Requires machinery & labor	Medium-High
Agroforestry diversification (Valencia et al., 2019; Jiren et al., 2020)	Integrated farmland	Moderate reductions; co-benefits outweigh	Lower nutrient runoff	Biodiversity ↑	Reduced exposure	Competes with intensive farming models	High

Review of Themes / Findings

Policy, Incentives, and Governance (Subsidies, Regulatory Design, Nutrient Footprints)

Policy instruments, incentive structures, and governance models significantly influence the success of climate mitigation strategies across material efficiency, food systems, and agroecosystems. Subsidies, regulatory exemptions, nutrient footprint frameworks, and integrated governance approaches determine both the scale and equity of outcomes. This section synthesizes the evidence presented in Table 4.4 and evaluates these instruments in light of the theoretical frameworks of systems nexus and the behavioral policy technology triad discussed in Section 3.

Impact of Subsidies and Regulatory Exemptions

Fossil Fuel Subsidies: Subsidies for fossil fuels are a persistent barrier to decarbonization. Allan et al. (2021) estimate that eliminating such subsidies could reduce global emissions by 20% by 2030. Stevenson et al. (2013) argue that fossil subsidies distort markets by promoting carbon-intensive fuels and delaying renewable transitions. This evidence aligns with the systems nexus perspective, where energy policies reverberate across food, materials, and ecosystems.

Agricultural Subsidies: Agricultural subsidies promoting monocultures encourage excessive fertilizer use, leading to emissions, soil degradation, and biodiversity loss (Khoo et al., 2015). Pătărlăgeanu et al. (2024) highlight how land expansion incentivized by subsidies drives deforestation. Such policies undermine the climate and biodiversity benefits of agroecological practices.

Regulatory Exemptions: Exemptions that relax standards for manufacturing or agriculture weaken climate policy effectiveness. L'Abbé et al. (2013) find that deregulation results in elevated emissions, creating sectoral loopholes. Lu et al. (2022) stress that counteracting these market distortions requires comprehensive policy reforms.

Nutrient Footprint Frameworks

Framework Effectiveness: Nutrient footprints quantify nitrogen (N) and phosphorus (P) flows and associated emissions. Lu et al. (2022) demonstrate that nutrient-based management reduces runoff and improves agricultural sustainability. Fallin et al. (2014) show how footprint metrics identify high-impact leakage zones for targeted interventions.

Policy Applications: Mokari-Yamchi et al. (2024) report improved water quality and reduced nutrient pollution in regions adopting nutrient footprint policies. Integrating nutrient metrics into agricultural planning enhances sustainability and farmer engagement (Zheng & Han, 2017).

Challenges: Despite benefits, implementation remains limited by data variability and complexity of nutrient cycles. Mokari-Yamchi et al. (2022) emphasize the need for standardized methodologies and accessible tools to engage diverse stakeholders.

Governance Models: Command-and-Control vs. Market-Based

Command-and-Control (CAC): CAC approaches rely on direct regulation and enforcement. Champagne (2019) and Zhu et al. (2024) show they achieve rapid compliance but risk rigidity. Industries often meet minimum standards without pursuing innovation.

Market-Based Approaches: Carbon pricing, emissions trading, and renewable subsidies incentivize innovation and long-term emissions reductions (Bulkeley & Betsill, 2013). Nweke (2011) and Liang (2016) provide evidence that market tools foster transformative change, especially when supported by robust institutional frameworks.

Comparative Effectiveness: Context matters. In strong governance systems, market-based approaches outperform CAC through efficiency and flexibility (Yang & Ding, 2024). In weaker governance contexts, CAC provides enforceable and predictable outcomes (Champagne, 2019).

Table 5. Policy Instruments and Outcomes for Climate Mitigation

Policy Instrument	Target / Sector	Outcome (GHG, air, nutrients, cost)	Leakage / Burden Shifting	Cost-effectiveness (per tCO₂e)	Implementation Context	Equity / Distribution Aspects	Evidence Quality
Fossil fuel subsidies (Allan et al., 2021; Stevenson et al., 2013)	Energy	Subsidies sustain high emissions	Cross-sector leakage	Removal cuts emissions by 20% (2030)	Global	Benefits affluent fossil users; harms poor via externalities	High
Agricultural subsidies (Khoo et al., 2015; Pătărlăgeanu et al., 2024)	Agriculture	Increased fertilizer, deforestation	Shifts emissions to land-use	High-cost inefficiency	Global, LMICs	Marginalizes smallholders	High
Regulatory exemptions (L'Abbé et al., 2013)	Industry, agriculture	Elevated emissions	Weakens mitigation	Low cost-effectiveness	National	Benefits large emitters	Medium-High
Nutrient footprint policies (Lu et al., 2022; Fallin et al., 2014; Mokari-Yamchi et al., 2024)	Agriculture	Reduced N/P runoff, better water quality	Limited shifting	Variable, depends on uptake	Regional	Enhances farmer engagement; equitable if inclusive	High
CAC governance (Champagne, 2019; Zhu et al., 2024)	Cross-sector	Immediate emission reductions	Risk of rigidity	Moderate	Global, developing regions	Compliance-based, limited equity focus	Medium-High
Market-based governance (Bulkeley & Betsill, 2013; Liang, 2016; Yang & Ding, 2024)	Cross-sector	Long-term transformative reductions	Leakage via trade	Cost-effective in robust systems	EU, OECD	Promotes innovation; risks inequity if not inclusive	High
Integrated equity-oriented policies (Myung & Lee, 2017; McGrath et al., 2025; Gupta et al., 2019; Suárez et al., 2024)	Multi-sector	Co-benefits: GHG, air, health	Potential leakage minimized with design	Variable	Global	Focus on justice; reduces disparities	High

DISCUSSION

The synthesis of findings across the four thematic areas material efficiency, food loss and waste (FLW) reduction with cold chain optimization, sustainable agroecosystems, and policy frameworks provides a comprehensive understanding of how integrated interventions can mitigate greenhouse gas (GHG) emissions while generating co benefits for biodiversity, human health, and equity. This discussion critically evaluates these findings, compares divergent outcomes, highlights methodological limitations, and elaborates on implications for theory, practice, and future research.

Cross-Domain Integration and Synergistic Potential

Material efficiency interventions, such as design for longevity, reuse, remanufacture, and lightweighting, demonstrate significant mitigation potential but are often constrained by rebound effects and consumer behavior (Milovanoff et al., 2019; Wu et al., 2019). Similarly, FLW reduction strategies show strong benefits for both emissions and health, but their effectiveness depends on the carbon intensity of the energy systems powering cold chains (Cheekatamarla et al., 2022; Berberian et al., 2024). Agroecosystem practices, including residue-based bioenergy and forest restoration, yield substantial climate and biodiversity benefits, though land competition and fire risks persist (Albanito et al., 2015; Sembhi et al., 2020). Policy and governance mechanisms act as cross-cutting enablers or barriers, influencing outcomes across all domains (Allan et al., 2021; Lu et al., 2022). Taken together, the evidence supports the hypothesis that integrated approaches across material, food, and agroecosystem systems produce greater climate benefits than isolated strategies.

Divergent Findings and Contextual Moderators

The reviewed studies underscore that outcomes vary significantly by context. In material efficiency, high-income countries (HICs) demonstrate greater reductions due to advanced recycling and technological capabilities, whereas low- and middle-income countries (LMICs) face barriers in infrastructure and governance (Mercure et al., 2014; Hao et al., 2022). In FLW and cold chain interventions, renewable powered refrigeration delivers net reductions, while fossil-fuel-based grids diminish benefits (Wang et al., 2020; Hu et al., 2021). This divergence reflects the moderating role of governance quality, infrastructure, and energy systems. For agroecosystems, land-free bioenergy consistently demonstrates high mitigation potential (Hanssen et al., 2019; Akkari et al., 2018), but trade-offs such as residue competition highlight that outcomes depend on local agricultural practices and resource availability (Koponen & Soimakallio, 2015). These variations reinforce the systems nexus perspective, showing that technological, behavioral, and policy conditions determine the success of interventions.

Trade-offs, Rebound Effects, and Unintended Consequences

Trade-offs and rebound effects are critical challenges across all domains. In material efficiency, lightweighting enhances vehicle fuel efficiency but may increase demand for resource-intensive materials such as aluminum, leading to upstream emissions (Modaresi et al., 2014). Similarly, design for longevity reduces replacement frequency but may slow technological innovation cycles (Milovanoff et al., 2019). In food systems, expanding cold chains reduces FLW but risks higher electricity demand, particularly in LMICs with carbon-intensive grids (Cheekatamarla et al., 2022). In agroecosystems, residue retention improves soil fertility but can elevate fire risks without proper management (Boutagayout et al., 2023; Sinaga et al., 2022). Policy domains also exhibit trade-offs: while carbon pricing drives innovation, it can create inequities if low-income households

bear disproportionate costs (Myung & Lee, 2017; McGrath et al., 2025). These findings highlight the importance of policy mixes that anticipate and mitigate rebound effects, aligning with the behavioral policy technology triad introduced in Section 3.

Research Gaps and Methodological Limitations

Despite growing evidence, significant gaps persist. First, many material efficiency studies rely on life cycle assessment (LCA) and integrated assessment models (IAMs), which, while robust, exhibit high sensitivity to assumptions such as grid mix and future technology pathways (Kelly et al., 2015; Elias & Thambiran, 2022). FLW reduction studies often lack precise quantification of avoided emissions and health outcomes, limiting comparability (Friedman Heiman & Miller, 2024; Gatto & Chepeliev, 2024). Agroecosystem research faces challenges in scaling results due to variability in soil types, climates, and management practices (Albanito et al., 2019; Arvesen et al., 2024). Policy evaluations suffer from a predominance of correlational rather than causal studies, limiting the ability to attribute outcomes directly to specific instruments (Champagne, 2019; Zhu et al., 2024). Moreover, equity analyses remain underdeveloped, with few studies systematically assessing the distribution of benefits and burdens across social groups (Suárez et al., 2024).

CONCLUSION

This systematic literature review examined the interconnected domains of material efficiency, food loss and waste reduction with cold chain optimization, sustainable agroecosystems, and policy governance. Across these four thematic areas, the evidence demonstrates that integrated interventions can substantially reduce greenhouse gas (GHG) emissions while delivering co-benefits for biodiversity, air quality, and human health. The findings collectively answer the research questions by showing that: (1) the net mitigation potential is greatest when material, food, and agroecosystem strategies are combined; (2) co-benefits include improved nutrient cycling, public health, and ecosystem resilience, though trade-offs and rebound effects must be managed; (3) contextual moderators such as energy mix, governance strength, and income levels critically shape outcomes; and (4) cross-domain policy portfolios are necessary to optimize results and ensure equity. The study contributes to knowledge by synthesizing fragmented evidence across environmental, technological, and policy domains, advancing the systems nexus perspective and the behavioral policy technology triad. Importantly, it highlights gaps in causal policy analysis, equity assessments, and harmonized metrics for multi-outcome evaluations. These limitations point to the need for more integrated, spatially explicit, and equity-oriented research. The review underscores that climate mitigation cannot be achieved through siloed approaches but requires holistic frameworks that align technological innovations, behavioral shifts, and policy reforms. By clarifying synergies and trade-offs, this work offers actionable insights for researchers, practitioners, and policymakers seeking to design effective, equitable, and resilient climate mitigation strategies.

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