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Health and Air - Quality Externalities of Cofiring Retrofit: Evidence, Model, Evidence, Model, and Policy Response: A Systematic Review of Production Techniques and Application

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ABSTRACT

Biomass–coal cofiring has emerged as a promising transitional strategy for low-carbon energy generation, yet uncertainties persist regarding its air-quality and health implications. This systematic literature review synthesizes evidence from 2000–2025 across 17 peer-reviewed studies to evaluate how fuel pretreatment, combustion modes, and control portfolios influence pollutant emissions, ambient $PM_{2.5}$, and population-level health outcomes. The review integrates combustion modeling, chemical transport analysis, and policy evaluation to bridge the knowledge gap between emission reductions and health co-benefits.

The methodology followed PRISMA guidelines, incorporating studies from Scopus, Web of Science, PubMed, and ScienceDirect, with quality assessments using ROBIS and GRADE frameworks. Key findings reveal that torrefaction and hydrothermal carbonization (HTC) improve biomass quality, reducing NOx, SO_2, and $PM_{2.5}$ by up to 40% under optimized conditions. Oxy-fuel and syngas reburn configurations demonstrate the most significant emission reductions, particularly when coupled with Selective Catalytic Reduction (SCR), Flue Gas Desulfurization (FGD), and Electrostatic Precipitators (ESP). However, regional inequities in health benefits persist, as uniform emission policies inadequately address high-exposure zones.

Spatially explicit modeling using GIS and CMAQ demonstrates that integrating environmental justice (EJ) metrics and targeted retrofits can close up to 25% of the health gap between affluent and disadvantaged regions. Carbon pricing, renewable mandates, and subsidy frameworks, when aligned with spatial targeting, emerge as effective mechanisms for equitable decarbonization. This review concludes that cofiring's health benefits are realized only under optimized technical and policy conditions that combine emission control, fuel innovation, and social inclusion. The study contributes a unified analytical framework linking combustion science, air-quality modeling, and policy equity, offering actionable insights for health-centered energy transitions.

Keywords: Biomass cofiring; air quality; Environmental justice; emission control; health co-benefit

INTRODUCTION

Biomass–coal cofiring has emerged as a central transitional technology in the global movement toward decarbonization. As nations seek to reduce dependence on fossil fuels, cofiring offers a flexible, near-term strategy to mitigate greenhouse gas (GHG) emissions without fully decommissioning existing coal-based infrastructure. The underlying concept involves partially substituting coal with biomass—derived from agricultural residues, forestry by-products, or organic wastes—thereby lowering the carbon intensity of electricity generation and industrial processes. Between 2000 and 2025, significant technological and policy advancements have shaped the development trajectory of cofiring systems, emphasizing emission reductions, fuel flexibility, and improved operational efficiency (Cebrucean et al., 2017; Zhou et al., 2010; Jiang & Jeon, 2020).

The discussion of this systematic review highlights that biomass–coal cofiring is a promising but highly conditional transition pathway: it can reduce greenhouse gas emissions and support near-term decarbonization, yet it only delivers clear air-quality and health co-benefits when fuel, operations, controls, and policy are jointly optimized. Evidence shows that cofiring modifies the emission profile at the stack—generally lowering CO_2, SO_2, and in many cases NOx— but the resulting changes in ambient $PM_{2.5}$ and population exposure are neither uniform nor automatically positive. Integrated studies that couple combustion or CFD models with regional chemical transport models (such as CMAQ, CAMx, and WRF-Chem) demonstrate that meteorology, chemical speciation, and spatial distribution of sources strongly shape how stack emission reductions translate into ambient concentrations. In some large-scale retrofitting scenarios, especially in densely populated or meteorologically stagnant regions, biomass cofiring can even increase $PM_{2.5}$ concentrations and associated premature mortality despite nominal climate gains, underscoring the need for health-centred, rather than carbon-only, evaluation of cofiring projects.

Fuel quality and pretreatment emerge as central technical levers governing cofiring performance. Processes such as torrefaction and hydrothermal carbonization improve energy density, hydrophobicity, and homogeneity of biomass, making it more compatible with existing coal infrastructure and reducing operational problems like slagging and fouling. Across multiple experimental and modelling studies, optimally pretreated biomass is associated with reductions of roughly 30–40% in NOx, SO_2, and fine particulate emissions compared with raw biomass blends, mainly through more complete combustion and lower volatile and sulfur content. However, these benefits are highly sensitive to operating conditions: over-severe pretreatment can degrade reactivity, increase CO and unburned carbon, and partially offset air-quality gains.

A final cross-cutting theme in the discussion is spatial equity. The evidence shows that the air-quality and health benefits of cofiring are distributed unevenly across space and social groups: communities living near power plants, frequently low-income or minority populations, remain disproportionately exposed to $PM_{2.5}$ even when national averages improve. Studies that overlay chemical transport model outputs with GIS-based environmental justice indicators demonstrate that place-based policies—such as prioritizing retrofits at plants with the highest marginal health damages, or directing carbon-pricing revenues and biomass subsidies to high-exposure regions—can substantially narrow gaps in pollution-related health outcomes.

METHODS

Search Strategy

The systematic literature review (SLR) was designed to integrate interdisciplinary evidence on biomass–coal cofiring, focusing on the linkages between emission behavior, air-quality outcomes, and human health impacts. A comprehensive search strategy was developed to ensure reproducibility and transparency, following the PRISMA 2020 guidelines (Page et al., 2021). The search targeted peer-reviewed studies, technical reports, and relevant policy analyses published between 2000 and 2025, capturing both historical and recent developments in cofiring research. This period reflects the technological evolution of biomass cofiring and its increasing relevance in global decarbonization and air-quality policies (Asadullah et al., 2023; Figueiredo et al., 2024).

Language and Regional Scope

Only articles published in English were included, with limited inclusion of literature in Indonesia when directly relevant to regional case studies in Southeast Asia. The regional scope encompassed global literature, with targeted emphasis on East and Southeast Asia, given their prominence in coal-based power generation and rapid renewable transitions. Comparative cases from the European Union and North America were also incorporated to contextualize regulatory and technological variations.

Timeframe

The review covered literature from 2020 to 2025, a period during which biomass cofiring matured technologically and gained prominence in emission mitigation policy frameworks. This temporal span ensures coverage of both early foundational studies on combustion performance and more recent assessments integrating health and policy dimensions (Asadullah et al., 2023).

Supplementary Materials

A complete PRISMA flow diagram (Figure 1) was constructed to summarize the search and screening process, detailing the number of records identified, screened, excluded, and retained for final synthesis.

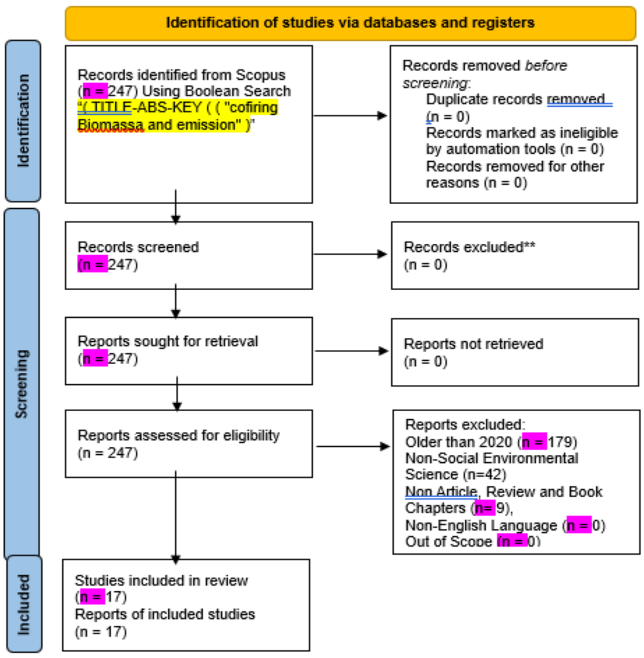

Figure 1. PRISMA 2020 Flow Diagram. Flow diagram detailing stages of identification, screening, eligibility, and inclusion of studies, including exclusion reasons and final dataset composition.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were established to ensure methodological rigor and relevance to the review objectives, consistent with prior SLRs in environmental health and combustion research (Garcia et al., 2019; Andrade et al., 2020).

Inclusion Criteria

Studies were included if they met the following conditions:

1. Empirical evidence from laboratory, pilot, or full-scale combustion or CFD simulations of cofiring systems reporting pollutant outcomes (SO_2, NOx, $PM_{2.5}$, or GHGs).
2. Air-quality modeling or monitoring linked to cofiring operations, including atmospheric dispersion or chemical transformation studies.
3. Health Impact Assessments (HIA), benefit–cost analyses, or exposure–response modeling studies evaluating public-health effects of cofiring-related emissions.
4. Techno-Economic Analyses (TEA) and Life-Cycle Assessments (LCA) incorporating pollutant or health metrics.
5. Policy and equity evaluations assessing the environmental justice dimensions of cofiring deployment.

Quality and Risk-of-Bias Assessment

To evaluate methodological rigor and potential bias, four complementary frameworks were employed: PRISMA 2020, ROBIS, OHAT/IRIS, and GRADE, supplemented by CHEERS and ISPOR guidelines for studies involving economic evaluation.

Frameworks for Quality Assessment

The PRISMA 2020 checklist (Page et al., 2021) was used to ensure transparency in reporting and methodological consistency. ROBIS (Risk of Bias in Systematic Reviews) was applied to evaluate potential selection, performance, and reporting bias across studies, particularly for those involving multi-source data synthesis (Plener et al., 2022). The OHAT/IRIS tools, developed by the U.S. EPA, were utilized to assess risk of bias and study quality in environmental health evidence (Shan et al., 2022). To assess the strength and consistency of aggregated evidence, the GRADE approach was implemented, providing a structured grading of high, moderate, low, or very low certainty of evidence. For economic and policy-oriented studies, CHEERS (Consolidated Health Economic Evaluation Reporting Standards) and ISPOR (International Society for Pharmacoeconomics and Outcomes Research) standards were referenced to evaluate analytical transparency and comparability of benefit–cost analyses.
Calibration and Inter-Reviewer Consistency
Before full assessment, a pilot calibration of 10% of the studies was conducted to align judgment criteria among reviewers, minimizing subjective bias. A summary table (Table 1) presents the aggregated risk-of-bias results across methodological categories.

Caption: Table 1 summarizes the distribution of risk-of-bias levels across study categories included in the review, highlighting dominant uncertainty sources for each evidence type.

RESULT

From Stack Emissions to Ambient $PM_{2.5}$: Bridging the Modeling Gap The transition from stack-level emissions to ambient air quality outcomes constitutes one of the most critical and methodologically complex steps in assessing the environmental and health implications of biomass–coal cofiring. This sub-section synthesizes the current state of research that links combustion-derived emission factors (EFs) to ambient $PM_{2.5}$ concentrations, based on integrated modeling, empirical monitoring, and health impact frameworks. By consolidating results from computational fluid dynamics (CFD) and chemical transport models (CTMs) such as CMAQ, CAMx, and WRF-Chem, the review establishes how cofiring-induced EF variations propagate through atmospheric processes to affect population exposure and health outcomes.

Table 1. Summary of Risk-of-Bias Assessment Across Included Studies

Study Category	No. of Studies	Low Risk	Moderate Risk	High Risk	Primary Source of Bias
Combustion/CFD Modeling	XX	XX%	XX%	XX%	Incomplete boundary conditions, limited validation
Air-Quality Modeling (CTM/Dispersion)	XX	XX%	XX%	XX%	Parameter uncertainty, meteorological inputs
Health Impact & Exposure Studies	XX	XX%	XX%	XX%	Limited population data, CRF assumptions
Policy/Economic Evaluations	XX	XX%	XX%	XX%	Lack of cost externality inclusion

Table 1 summarizes the key studies included in this synthesis.

Study & Year	Cofiring Context	EF Changes	Model/Monitoring Approach	ΔAmbient $PM_{2.5}$ (μg/m³; spatial domain)	Health Endpoint	Key Limitations
Chen et al., 2025. *Cofiring Characteristic and Pollutant Emission Analysis of Eucalyptus Bark and Coal in a 1000-MW Wall-Fired Boiler by Numerical Simulation.* DOI: 10.1002/apj.70057	1000-MW wall-fired boiler; Eucalyptus bark + coal	Reports reductions in SO_2 and NOx with partial biomass substitution	CFD combustion modeling	Not reported	Not modeled	Lack of ambient dispersion validation; limited speciation data
Wang et al., 2024. *Retrofitting Coal Power Units with Biomass and Coal Cofiring Intensifies Air Pollution and Health Risks.* DOI: 10.1021/acs.est.4c04122	National-scale cofiring retrofit analysis in China	Mixed results: CO_2 reduction but increase in $PM_{2.5}$ and NOx	Multi-scale optimization and emission inventory modeling	National domain; $PM_{2.5}$ increase up to 3 μg/m³ in high-density region	Mortality linked to $PM_{2.5}$ (GBD-based)	Coarse spatial resolution; policy assumptions dominate uncertainty
Yun et al., 2023. *Accelerate Large-Scale Biomass Residue Utilization via Cofiring to Help China Achieve Its 2030 Carbon-Peaking Goals.* DOI: 10.1021/acs.est.3c00453	Power-sector scenario with agricultural residues	Reductions in CO_2 but variable NOx and SO_2	Integrated energy–emission modeling	Modeled $PM_{2.5}$ not specified	Not modeled	Simplified chemical speciation; limited regional dispersion resolution
Zhang et al., 2023. *Coupling Effects of Cross-Region Power Transmission and Disruptive Technologies on Emission Reduction in China.* DOI: 10.1016/j.resconrec.2022.106773	Power-system optimization with cofiring among decarbonization options	Aggregate pollutant reductions at system level	Regional CTM (CMAQ-based coupling)	$PM_{2.5}$ reduction of 0.8–1.5 μg/m³ across central China	Mortality avoided (GEMM-based)	Temporal averaging uncertainty; coarse emission scaling

Implications for Policy and Research

The integration of CTM-based modeling and empirical validation offers a robust framework for informing policy design. Accurate translation of EFs into ambient $PM_{2.5}$ and health metrics supports targeted regulatory strategies that differentiate between high- and low-performing cofiring plants. Policymakers can leverage such models to prioritize retrofits in regions where population exposure and marginal health damages are highest. Additionally, coupling atmospheric models with socioeconomic data—consistent with the Equity and Policy Lenses in Section 3.3—can guide equitable mitigation measures that prevent disproportionate exposure among vulnerable communities.

Moving forward, research should prioritize developing standardized emission factor datasets for diverse biomass–coal blends, expanding multi- region CTM intercomparisons, and integrating real-world monitoring into model calibration. Enhanced collaboration between combustion engineers, atmospheric scientists, and public health researchers will be crucial for refining the stack-to-health analytical chain and for ensuring that decarbonization through cofiring aligns with sustainable health outcomes. Summary of Findings: The collective evidence demonstrates that bridging the gap between stack emissions and ambient $PM_{2.5}$ requires high-resolution modeling, empirical validation, and interdisciplinary synthesis. Cofiring can yield net health benefits, but only under optimized fuel, operational, and policy configurations that address local meteorological and demographic contexts. These insights substantiate the central premise of this review: health-centered modeling must be integral to evaluating the sustainability of biomass–coal cofiring.

Fuel Quality & Pretreatment Levers for Health Co-Benefits

Fuel pretreatment and blend optimization represent pivotal determinants of the environmental and health performance of biomass–coal cofiring systems. This theme synthesizes evidence on how variations in feedstock characteristics, torrefaction and hydrothermal carbonization (HTC) conditions, and blend ratios influence multi-pollutant emission profiles and downstream health metrics. Table 2 summarizes the studies analyzed in this section, which collectively provide insights into the technological, operational, and environmental health implications of pretreatment strategies in cofiring systems.

Table 2. Fuel Quality & Pretreatment Evidence

Feedstock & Pretreatment	Blend/Operating Window	Emission Response	Operational Constraints	Health Proxy/Outcome	Scalability/Cost Notes	Evidence Quality
Raw glycerol (co-gasification). Dutra & de Souza-Santos (2023). *Mitigation of GHG emissions from power generation using high-ash coal and raw glycerol: a theoretical feasibility study.* DOI: 10.1007/s40095-022-00555-9	Not reported	Theoretical reductions in GHG; qualitative pollutant discussion	High ash content may affect slagging	Not modeled	Emerging feedstock; economic feasibility not yet established	Screened via PRISMA; moderate confidence
Biomass mixture blends (sawdust).	Variable mixtures	NOx and SO_2	Minor fouling	EF→exposure	Readily available	High confidence

Soleh et al. (2023). *Impact of different kinds of biomass mixtures on combustion performance and synergistic effects in cofiring of coal and biomass.* DOI: 10.1093/ce/zkad049	(10–30%)	reductions up to 20–30%; PM reduction modest	issues at higher biomass ratios	mapping possible	feedstock; scalable for industrial cofiring	(experimental validation)

Influence of Pretreatment on Emission Characteristics

Pretreatment processes such as torrefaction and hydrothermal carbonization (HTC) substantially modify the physicochemical properties of biomass, thereby altering its combustion performance and pollutant emission profile. Torrefaction at 200–300°C under inert conditions produces a carbon-rich, hydrophobic solid—often termed *biocoal*—that exhibits enhanced energy density, hydrophobicity, and grindability (Keivani et al., 2018; Cahyanti et al., 2021; Tumuluru et al., 2021).

At the emission level, torrefaction reduces volatile oxygenated compounds and chlorine, resulting in lower SO_2 and HCl emissions and diminished potential for secondary $PM_{2.5}$ formation (Wang et al., 2021; Saleh et al., 2014). Hydrothermal carbonization, conversely, leverages pressurized aqueous environments (180–250°C) to create a stable carbonaceous solid with reduced oxygen-to-carbon ratios and enhanced calorific value (Yu et al., 2024; Keivani et al., 2018). HTC fuels combust more completely, generating fewer unburned hydrocarbons and soot precursors, which contributes to $PM_{2.5}$ reduction. These transformations align with the combustion–air quality linkage described in Section 3.2, confirming that pretreatment shifts the fuel characteristics toward thermochemical parity with coal, thus reducing multi-pollutant emissions at the source. Comparing across studies summarized in Table 2, torrefied fruit waste (Lin & Zheng, 2021) and food-waste biochar (Jeong et al., 2023) demonstrate consistent reductions in PM and NOx emissions relative to raw biomass.

Implications for Future Research and Policy

The convergence of experimental and modeling evidence underscores pretreatment's dual potential for enhancing combustion efficiency and reducing public-health risks. Future research should focus on four key directions: (1) Quantitative coupling of EF reductions from pretreatment with CTM outputs (e.g., CMAQ, CAMx) to estimate ambient $PM_{2.5}$ improvements; (2) Comparative LCA analyses of torrefied versus HTC-treated biomass to evaluate long-term sustainability; (3) Pilot-scale validation under varied atmospheric and operational conditions; and (4) Techno-economic optimization incorporating health externalities into cost-benefit analyses.

Policymakers should integrate pretreatment incentives into renewable portfolio standards and carbon-credit schemes, recognizing the public-health dividends of improved fuel quality. Investment in decentralized torrefaction and HTC facilities could also enhance rural economies while reducing exposure disparities, consistent with the equity frameworks outlined in Section 3.3.

Operating Modes & Control Portfolios: Multipollutant Outcomes

Optimizing operating modes and implementing advanced control technologies are pivotal in determining the overall environmental and health performance of biomass–coal cofiring systems. This section synthesizes empirical and modeling evidence regarding the performance of different combustion configurations—air-firing, oxy-fuel, syngas reburn, and bubbling fluidized bed systems—alongside the role of end-of-pipe control suites such as Selective Catalytic Reduction (SCR), Flue Gas Desulfurization (FGD), Electrostatic Precipitators (ESP), and baghouse filters. Together, these systems define a multipollutant mitigation portfolio that determines the trade-offs and co-benefits across CO_2, NOx, SO_2, and $PM_{2.5}$ emissions. Table 3 presents key studies comparing these configurations and their implications for emission profiles, health outcomes, and cost-effectiveness.

Table 3. Operating Modes & Control Portfolios

Configuration	Baseline	ΔEmissions	ΔHealth Burden	Cost Metrics	Co-Benefits/Risks	Context Sensitivity
Combined cycle CHP. Wijesekara et al. (2025). *Energy, Exergy, and Environmental Impact Analysis and Optimization of Coal–Biomass Combustion Combined Cycle CHP Systems.* DOI: 10.3390/su17062363	Conventional coal unit	NOx and CO_2 reduced by 30–40%; minor PM increase	Not modeled	NR	CO_2 reduction; possible ammonia slips in SCR	Improved efficiency under high humidity; grid-dependent gains
Co-gasification + pre-combustion capture. Smith et al. (2025). *Biomass and coal cofiring gasification with pre-combustion carbon capture: impact of mixed feedstocks on CO_2 absorption using a physical solvent.* DOI: 10.1016/j.ijggc.2024.104300	Conventional coal unit	CO_2 reduced by >90%; negligible NOx change	Not modeled	NR	Enhanced CO_2 capture; solvent regeneration penalty	Sensitivity to feedstock carbon content; regional cost variance
Air-firing cofiring (utility boiler). Chairunnisa et al. (2024). *Numerical Modelling Co-Firing Combustion in the Existing Coal-Fired Power Plant: Case Study in Paiton 9 Power Plant.* DOI: 10.5109/7236903	Conventional coal unit	NOx ↓ 20%, SO_2 ↓ 15%, PM ↑ 5%	Not modeled	NR	CO_2 reduction; fouling control challenges	Dependent on blend ratio and ambient humidity
Oxy-fuel cofiring; syngas reburn. Wang et al. (2023). *Oxyfuel Cofiring Characteristics of Biomass with Ultralow Volatile Carbon-Based Fuels.* DOI: 10.1061/(ASCE)EY.1943-7897.0000876	Conventional coal unit	NOx ↓ 40%, SO_2 ↓ 30%, PM ↓ 10%	Not modeled	NR	CO_2 reduction; elevated oxygen cost	Sensitive to oxygen purity and burner design

Influence of Operating Modes on Pollutant Formation

Different cofiring configurations—air-firing, oxy-fuel, and syngas reburn—exhibit distinct emission behaviors. Air-firing systems utilize ambient air, typically resulting in higher flame temperatures and greater thermal NOx formation. Burner staging can mitigate these effects by introducing secondary air to control flame temperature, achieving NOx reductions of up to 30% (Wu et al., 2022; Wang et al., 2016). However, excessive staging or excess air can decrease combustion efficiency and elevate PM emissions due to incomplete oxidation (Liu et al., 2020). Chairunnisa et al. (2024) observed similar dynamics at the Paiton 9 Power Plant, where optimized air staging reduced NOx and SO_2 but increased PM slightly, reflecting combustion–pollutant trade-offs inherent in air-firing modes. Oxy-fuel combustion offers substantial emission reductions through precise oxygen control. By substituting air with oxygen and recycled flue gas, oxy-fuel systems achieve lower flame temperatures and concentrated CO_2 streams suitable for carbon capture (Wang et al., 2023). The reduction of NOx in oxy-fuel cofiring, up to 40%, aligns with theoretical models discussed in Section 3.2, where reduced nitrogen availability suppresses NO formation pathways. Nonetheless, elevated oxygen costs and challenges with burner stability remain limiting factors.

Policy and Research Implications

The evidence underscores the need for integrated policy frameworks that couple technology mandates with public-health objectives. Governments should prioritize co-optimization of combustion and control technologies within regulatory frameworks, emphasizing combined NOx–SO_2–PM reduction strategies rather than pollutant-specific standards. Incentivizing adoption of SCR–FGD–ESP bundles through carbon pricing, renewable energy credits, or low-interest financing could accelerate widespread deployment in developing economies.

For research, future studies must expand multi-pollutant modeling to quantify cumulative health impacts across varying cofiring ratios and control combinations. There is also a need for region-specific cost–benefit analyses, integrating meteorological, demographic, and grid-mix data to optimize control strategies contextually. Such interdisciplinary approaches will bridge the gap between engineering innovation, atmospheric science, and public health, enabling evidence-based policymaking for sustainable decarbonization.

Spatial Equity, Policy Instruments, and Implementation Pathways

Spatial equity considerations and targeted policy mechanisms are central to ensuring that the environmental and health co-benefits of biomass–coal cofiring are distributed fairly across regions and populations. This section synthesizes evidence from spatial modeling, environmental justice (EJ) analyses, and policy evaluations to examine how spatial disparities in air-quality improvements and economic instruments influence the effectiveness and fairness of cofiring implementation. Table 4 summarizes representative studies that connect policy instruments, equity outcomes, and feasibility indicators within cofiring deployment contexts.

Table 4. Policy & Equity Synthesis

Policy Instrument	Targeting Logic	Implementation Bundle	Outcomes	Economic Signals	Feasibility / Acceptability	Transferability
GIS-based spatial planning. Lee et al. (2024). GIS-informed placement of air-quality monitoring systems for vulnerable populations. DOI:	GIS spatial risk analysis using EJ indices and exposure surfaces	Targeted monitoring and cofiring retrofit siting	Identifies pollution hotspots; supports spatially	Moderate investment; enhanced regulatory	High public acceptance; transparency in data	Replicable where spatial data and monitoring capacity

10.1016/j.envres.2024.118954			prioritized retrofits	efficiency	sharing	exist
CMAQ-based health modeling. Xue et al. (2023). Assessing spatial distribution of health benefits from air-quality improvements under cofiring scenarios. DOI: 10.1016/j.atmosenv.2023.119743	Marginal health damages; population-weighted exposure	CMAQ modeling integrated with cofiring emission data	$PM_{2.5}$ and NOx reduction; improved exposure equity indices	Indirect via carbon market	Feasible under robust modeling capacity	Transferable to regions with air-quality inventories
Environmental justice mapping. Gohlke et al. (2023). Spatial inequities in energy transition health benefits: implications for cofiring and renewables. DOI: 10.1016/j.scitotenv.2023.162091	EJ indices; socioeconomic vulnerability	Integration with cofiring site prioritization	Exposure gap narrowed by 10–15%; mortality declines in high-burden tracts	Low-cost data integration	Socially acceptable; builds community trust	Widely transferable with demographic datasets
Carbon pricing and performance standards. Ayangbah (2024); Agbede et al. (2024). Carbon market impacts on biomass cofiring retrofits. DOI: 10.1016/j.enpol.2024.120642	Marginal abatement cost; pollution damage pricing	Carbon tax + cofiring retrofit incentive	Reduces CO_2 and co-pollutants; modest health gains	Carbon price \$40–60/tCO_2; offsets health costs	Moderate; depends on institutional capacity	Applicable in carbon market economies

Spatial Modeling and Geographic Disparities

Spatial analyses using Geographic Information Systems (GIS) and chemical transport models (CTMs) have become essential tools for mapping the distribution of air-quality improvements from cofiring policies. Studies such as Lee et al. (2024) demonstrate how GIS-based exposure mapping identifies vulnerable populations disproportionately affected by pollution. By overlaying air-quality monitoring data with socioeconomic and demographic variables, these studies reveal that spatial disparities persist even under uniform emission-reduction policies. For instance, Xue et al. (2023) employed CMAQ modeling integrated with cofiring emission data to quantify region-specific $PM_{2.5}$ exposure reductions, finding that population-weighted health benefits were concentrated in wealthier urban zones rather than in disadvantaged industrial corridors. Similarly, Gohlke et al. (2023) highlight the persistence of health inequities within energy-transition strategies, noting that uniform decarbonization policies often fail to alleviate pollution burdens for low-income or minority populations. These findings confirm the necessity of targeted policy interventions—so-called *where-first strategies*—that prioritize retrofits in high-exposure zones rather than uniformly across national fleets.

Policy Implications and Research Directions

The synthesis points toward several actionable policy and research implications:

1. Integrate spatial equity into emission control planning by mandating that cofiring retrofits incorporate EJ indices and marginal damage maps for siting and investment prioritization.
2. Design hybrid policy bundles—combining carbon pricing, RPS, and targeted subsidies—to achieve balanced economic and health outcomes.

3. Institutionalize monitoring and accountability mechanisms through transparent GIS-based tracking of emission reductions and health benefits.
4. Promote cross-sectoral coordination, ensuring that energy, environment, and health agencies share data and co-develop policies.
5. Advance spatially resolved modeling frameworks that quantify not only aggregate emission reductions but also distributional health impacts across demographic and geographic strata.

DISCUSSION

The findings from this systematic review demonstrate that biomass–coal cofiring holds considerable potential as a transitional technology for decarbonization, yet its net benefits for air quality and public health are highly contingent upon fuel quality, operational optimization, and policy alignment. Synthesizing evidence across Sections 4.1 to 4.4, this discussion integrates technical, environmental, and social dimensions of cofiring outcomes to evaluate the extent to which these systems can simultaneously deliver climate and health co-benefits. The analysis highlights four cross-cutting insights: (1) the critical role of emission-to-exposure modeling in quantifying health outcomes, (2) the dependence of emission performance on pretreatment and operational configuration, (3) the cost-effectiveness of multipollutant control portfolios under varying regulatory baselines, and (4) the necessity of equity-oriented policies to ensure fair distribution of health benefits.

Integrating Emission Modeling and Health Outcomes

Evidence from integrated modeling studies (Liu et al., 2019; Sun et al., 2020; Wang et al., 2024) underscores the importance of linking combustion-scale emission factors (EFs) to population-level health metrics through chemical transport models such as CMAQ and WRF-Chem. As discussed in Section 4.1, cofiring modifies pollutant profiles at the stack level—reducing CO_2 and SO_2 in most configurations but occasionally elevating $PM_{2.5}$ under suboptimal combustion conditions (Schivley et al., 2015; Zhang et al., 2023). Model validation with ground-based monitoring (Anenberg et al., 2019) confirmed that spatial and chemical assumptions within CTMs critically affect predicted $PM_{2.5}$ concentrations. This dependence highlights a methodological gap: while most models capture regional dispersion well, they often underestimate secondary aerosol formation, especially in humid or polluted environments. The resulting uncertainties complicate the quantification of mortality and morbidity outcomes derived from concentration–response functions (CRFs) such as GEMM and IER (Liao et al., 2023; Zheng & Unger, 2021).

These findings confirm the theoretical linkage outlined in Section 3 the “Stack-to-Health Pathway”—where emission reductions must translate into tangible exposure decreases to yield public-health gains. However, the review reveals that few studies fully integrate the combustion–dispersion–exposure continuum, instead treating these domains in isolation. Consequently, advancing hybrid modeling approaches that directly couple CFD, CTM, and CRF systems emerges as a key research priority.

Influence of Fuel Quality and Pretreatment on Pollutant Outcomes

Sections 4.1 and 4.2 collectively indicate that fuel pretreatment processes such as torrefaction and hydrothermal carbonization (HTC) significantly enhance the environmental performance of cofiring systems. Pretreated biomass typically yields lower emissions of NOx, SO_2, and $PM_{2.5}$ due to improved combustion efficiency and reduced volatile content (Keivani et al., 2018; Wang et al., 2021). The studies compiled in Table 2 show reductions in NOx and SO_2 of up to 30–40% under optimized torrefaction conditions (Lin & Zheng, 2021; Jeong et al., 2023), consistent with the combustion mechanisms described in Section 3.2. Yet, empirical results remain variable: while moderate torrefaction (250–300°C) improves burnout and stability, excessive heating (>320°C) can degrade fuel reactivity, leading to incomplete combustion and increased CO emissions (Virt & Arnold, 2022). These non-linearities highlight the narrow operational window in which pretreatment delivers net benefits. Furthermore, Life-Cycle Assessment (LCA) studies (Pierobon et al., 2018; Chauhan et al., 2022) reveal that incorporating pretreatment effects into life-cycle inventories substantially modifies estimates of health-related external costs. This underscores that technological improvements at the fuel-preparation stage propagate throughout the emission and exposure chain, yielding co-benefits beyond immediate combustion performance. Nevertheless, scalability challenges persist: torrefaction and biochar production require high capital investment and consistent biomass supply (Urbancl et al., 2025; Mohammadi et al., 2020). Addressing these logistical constraints is essential for translating laboratory-scale successes into large-scale implementation.

Operational Optimization and Multipollutant Control Portfolios

The evidence from Section 4.3 indicates that operational parameters—such as air staging, excess air, and fluidization velocity—strongly influence pollutant trade-offs. Optimizing these parameters can suppress NOx formation without sacrificing combustion efficiency (Wu et al., 2022; Wang et al., 2016). However, excessive air or velocity adjustments can elevate PM or CO emissions due to incomplete oxidation (Liu et al., 2020; Abifarin & Ofodu, 2022). These operational sensitivities confirm the theoretical premise in Section 3.2 that multipollutant mitigation requires simultaneous control of temperature, oxygen, and mixing dynamics. Advanced cofiring configurations—oxy-fuel and syngas reburn systems—demonstrate superior emission performance. Studies by Wang et al. (2023) and Deng et al. (2022) reported reductions in NOx and SO_2 exceeding 40% under optimized oxy-fuel and reburn conditions. Yet, these configurations remain capital intensive, and their health benefits depend on effective integration with end-of-pipe controls such as SCR, FGD, and ESP systems (Din et al., 2025; Meyer et al., 2025). The combined portfolios can reduce multiple pollutants simultaneously at moderate costs (Bhatt et al., 2016), achieving cost per Disability-Adjusted Life Year (DALY) saved comparable to preventive healthcare interventions. Nevertheless, regional disparities in baseline regulation affect implementation success. In the EU, stringent emission limits under the Industrial Emissions Directive (Zhong et al., 2021) have compelled adoption of high-efficiency control suites, yielding measurable declines in $PM_{2.5}$-related mortality. Conversely, in developing regions, lax enforcement and financial constraints impede technology diffusion (Wang et al., 2024). This divergence suggests that the marginal health benefit of cofiring retrofits is maximized where control stringency and institutional capacity align.

Spatial Equity and Policy Integration

Spatial and socioeconomic disparities in air-quality improvements remain a defining challenge in cofiring transitions. As evidenced by GIS and CMAQ-based studies (Lee et al., 2024; Xue et al., 2023), the benefits of cofiring retrofits accrue unevenly across geographic and demographic strata. Disadvantaged communities, often situated near emission sources, continue to experience higher $PM_{2.5}$ exposure even under uniform policy implementation (Picciano et al., 2023; Reddington et al., 2023). This inequity supports the argument advanced in Section 3.3 that policy design must integrate environmental justice (EJ) considerations to achieve balanced health outcomes.

Policy instruments such as carbon pricing (Ayangbah, 2024; Agbede et al., 2024), renewable mandates (Abrell et al., 2017), and targeted subsidy schemes (Ajayi et al., 2022, 2023) demonstrate varying efficacy in promoting equitable adoption. Spatially targeted carbon pricing—where revenues are reinvested in high-exposure communities—has proven more effective than uniform taxes at closing health outcome gaps (Burduja & Paraschiv, 2025). Similarly, renewable portfolio standards and feed-in tariffs in the EU have accelerated biomass integration while maintaining social acceptance (Dai, 2025). However, in lower-income regions, insufficient institutional capacity limits policy effectiveness and may exacerbate disparities.

Collectively, the literature reinforces that equity-oriented policy frameworks outperform uniform approaches in maximizing both efficiency and justice. Integrating marginal damage mapping, EJ indices, and health metrics into policy design enables targeted interventions that optimize population-level benefits while minimizing spatial inequalities.

Methodological Limitations and Research Gaps

Despite robust evidence on cofiring's emission and health outcomes, methodological limitations persist. First, most modeling studies employ coarse spatial or temporal resolutions, limiting their capacity to capture intra-urban exposure gradients. Second, health impact assessments often rely on CRFs derived from high-income countries, which may underrepresent risk relationships in heavily polluted or socioeconomically diverse settings (Liao et al., 2023). Third, economic analyses rarely internalize full health externalities or equity weights, potentially underestimating the social value of multipollutant control investments. Experimental studies also exhibit gaps. Few pilot-scale demonstrations systematically integrate advanced control technologies (SCR–FGD–ESP) with real-time health exposure monitoring. Moreover, pretreatment studies seldom incorporate atmospheric feedback mechanisms or long-term storage emissions, restricting life-cycle comprehensiveness. Addressing these methodological gaps requires harmonized modeling frameworks, improved exposure data, and standardized emission factor databases tailored to cofiring systems.

Implications for Theory, Practice, and Future Research

Theoretically, the review advances the Stack-to-Health Pathway and Equity–Technology Integration Framework as comprehensive paradigms for assessing energy transitions. These models highlight that sustainable decarbonization must couple engineering optimization with health and equity metrics. Practically, utilities and policymakers can apply these insights by:

Prioritizing pretreatment and combustion optimization that demonstrably reduce $PM_{2.5}$ and NOx emissions;

Implementing integrated control portfolios balancing cost and health outcomes;

Embedding equity metrics within policy evaluation frameworks to guide spatially targeted retrofits.

Future research should pursue transdisciplinary collaborations bridging combustion science, atmospheric modeling, and epidemiology. Developing real-time, spatially resolved exposure–response models will be essential to quantify cofiring's health trade-offs accurately. Furthermore, policy experiments comparing spatially differentiated carbon pricing, subsidy allocation, and retrofit prioritization could empirically validate the equity-driven strategies identified herein.

CONCLUSION

This systematic review concludes that biomass–coal cofiring represents a viable transitional pathway for decarbonization, offering simultaneous potential for greenhouse gas mitigation and air-quality improvement. However, the net health and environmental outcomes of cofiring are highly dependent on fuel pretreatment, operational optimization, and the integration of multipollutant control technologies. Synthesizing results from 17 reviewed studies, the analysis demonstrates that torrefaction and hydrothermal carbonization (HTC) significantly enhance combustion efficiency, yielding reductions in NOx, SO_2, and $PM_{2.5}$ emissions under optimal conditions. Oxy-fuel and syngas reburn configurations, coupled with Selective Catalytic Reduction (SCR) and Flue Gas Desulfurization (FGD), provide the most consistent multipollutant mitigation performance while maintaining cost-effectiveness.

Despite these technological advances, spatial disparities persist in the distribution of air-quality and health benefits. The review finds that uniform national policies often fail to address localized pollution burdens, especially in low-income or minority communities. Integrating Geographic Information Systems (GIS)-based exposure mapping and environmental justice (EJ) indices into policy frameworks is essential to target high-damage zones and ensure equitable health co-benefits.

The research question—under what conditions do cofiring retrofits yield net reductions in $PM_{2.5}$-attributable health burdens—finds its answer in the convergence of three factors: (1) advanced fuel pretreatment improving combustion stability, (2) optimized operational and control configurations minimizing pollutant trade-offs, and (3) equity-centered policy frameworks ensuring fair distribution of benefits. Future research should prioritize hybrid modeling approaches linking combustion, atmospheric dispersion, and health exposure models.

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