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Review Paper

Coal-Biomass Cofiring Beyond Feasibility: Compatibility Mapping, Ash Chemistry, Corrosion Control, and Digital Plant Optimization: A Literature Review

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ABSTRACT

Coal-biomass cofiring is no longer best understood as a simple fuel-substitution measure; it has become a multi-criteria engineering problem in which feedstock compatibility, ash chemistry, combustion dynamics, corrosion, digital control, logistics, and environmental accounting interact across scales. Building upon recent studies on coal-biomass cofiring, this article develops a publication-oriented synthesis of the current evidence base with emphasis on advances reported between 2020 and 2026. The review shows that the decisive question is not whether cofiring can reduce fossil dependence, but under what coal-biomass combinations, blending windows, and operating conditions those benefits can be realized without unacceptable penalties in slagging, fouling, corrosion, derating, or cost. Across the new literature, several important shifts are evident: compatibility screening is moving from generic biomass categories toward species- and residue-specific assessment; ash-risk diagnosis is increasingly based on integrated indices, thermodynamic modeling, and post-combustion characterization; digital tools such as flame-image convolutional neural networks and recurrent-neural-network optimization are entering plant practice; and environmental evaluation is expanding from stack emissions to life-cycle and circular-economy perspectives. The updated evidence further shows that some biomasses improve ash behavior or emissions, whereas others promote low-melting phases, chlorine-driven corrosion, unstable milling, or moisture-related derating. This review organizes the available studies into a decision framework for fuel qualification, blend-ratio selection, ash and corrosion management, and plant-level optimization. It argues that the next phase of cofiring research should move toward compatibility-based fuel approval, dynamic and data-rich control, and integrated metrics that jointly assess emissions, reliability, economics, and downstream ash utilization.

Keywords: coal-biomass cofiring; ash chemistry; slagging and fouling; boiler corrosion; digital combustion optimization; pulverized coal-fired power plants; decarbonization transition

INTRODUCTION

Coal-biomass cofiring continues to occupy an important place in the transition literature because it can be implemented in existing coal-based assets while partially reducing fossil fuel use, greenhouse-gas intensity, and selected conventional emissions when the fuel combination and combustion conditions are favorable [1]-[4]. That transitional appeal is the reason cofiring appears repeatedly in policy, engineering, and operations studies across Asia, Europe, and other coal-dependent regions [5]-[7]. Yet the literature supplied in RIS makes equally clear that the field has moved beyond a generic feasibility narrative. In current studies, the central issue is no longer whether biomass can be blended with coal in principle, but which biomasses can be blended with which coals, at what fraction, with what pretreatment, under which furnace settings, and with what consequences for ash behavior, tube life, derating, cost, and life-cycle impact [8]-[10]. This shift matters because biomass is not a single engineering material. The updated evidence base includes woody biomasses such as acacia, mahogany, pine sawdust, birch, larch, and carbonized wood pellets; agro-residues such as empty fruit bunch, palm frond, rice husk, corn husk, mesocarp fiber, poultry manure, and palm kernel shell; mixed wastes such as organic refuse-derived fuel and solid recovered fuel; and broader residue streams such as autumn tree leaves and sawdust produced at utility scale [2], [11]-[14]. These resources differ in heating value, moisture content, grindability, ash composition, chlorine and alkali content, and transport behavior, so they cannot be assumed to create equivalent furnace outcomes [3], [8], [15]. The practical meaning of cofiring has therefore changed: it is less a generic “renewable blend” problem and more a compatibility-and-control problem.

The recent literature also shows that cofiring research has become methodologically richer. Studies now combine ash indices, ash fusion temperatures, scanning electron microscopy with energy-dispersive spectroscopy, X-ray diffraction, X-ray fluorescence, drop-tube furnace tests, computational fluid dynamics, flame-image recognition, recurrent neural networks, life-cycle assessment, mixed-integer optimization, and techno-economic analysis [4], [16]-[19]. This convergence reflects the fact that fuel blending affects multiple tightly linked variables at once: ignition and devolatilization, flame stability, pollutant formation, deposit stickiness, corrosion mechanisms, milling performance, stockyard moisture, and economic dispatch [3], [11], [20]. For a top-tier review article, it is therefore insufficient to summarize only decarbonization potential or combustion chemistry in isolation. The updated synthesis must connect fuel science, boiler materials, plant operation, and sustainability assessment into one analytical frame.

This review synthesizes recent studies on coal-biomass cofiring and argues that four propositions increasingly define the field: pair-specific biomass-coal compatibility is more important than generic feedstock availability; ash chemistry remains the primary technical boundary of implementation; digital and operational intelligence increasingly determine stable plant performance; and system-level sustainability must be evaluated through broader environmental and economic boundaries.

LITERATURE REVIEW

Feedstock landscape and the move from generic biomass to compatibility mapping

The strongest update visible in the recent literature is the decline of generic biomass thinking. Early policy and review discourse often treated biomass as a relatively uniform renewable substitute for coal, differing mostly in moisture content or heating value. The extracted recent studies instead show that species-specific and residue-specific mineralogy can fundamentally reshape combustion and ash outcomes [2], [8], [10]. The practical implication is that “availability” is not enough for fuel approval. A biomass may be cheap, abundant, and politically attractive but still technically unsuitable if its ash chemistry or chlorine content creates unacceptable deposition or corrosion behavior [13], [15], [21].

Palm oil residues illustrate this point well. Two 2021 review-oriented studies highlight the abundance and underutilization of empty fruit bunches, mesocarp fiber, and palm kernel shell while also emphasizing the need to understand feedstock characteristics before cofiring is scaled [2], [22]. That recommendation is reinforced by later experimental work. Hariana et al. [8] showed that cofiring pulverized coal with 25% empty fruit bunch or palm frond increased slagging tendency, reduced ash fusion temperatures, and increased sticky deposits on the probe, even though the blend had attractive combustion performance. Hariana et al. [12] confirmed in a dedicated ash-deposit study that 25% palm-oil-waste cofiring altered ash composition and increased slagging, although a 50:50 blend of empty fruit bunch and frond performed better than single-biomass cases. The important lesson is not that palm residues are unsuitable in general, but that they require chemistry-aware qualification and perhaps blending strategies that exploit internal complementarity between residues [2], [12], [23].

The contrast between acacia and mahogany makes the case for compatibility mapping even more sharply. Suyatno et al. [10] investigated cofiring with up to 40% woody biomass and showed that acacia produced a cleaner ash profile on the slagging probe than mahogany. The poorer performance of mahogany was linked to anorthite-related low-melting phases that generated ash-related concern, even though both fuels belonged to the broad category of woody biomass [10]. This finding undermines any attempt to use broad categories such as “wood biomass” as a sufficient decision basis. Species-level mineralogy and the resulting phase transformations matter more than category labels. Similar caution emerges in the eucalyptus-bark study, where Chen et al. [21] showed increased particle size, sintering, adhesion, and severe slagging tendency in selected biomass-coal combinations. In short, the current literature replaces generic feedstock optimism with pairwise compatibility thinking.

Not all biomass additions worsen ash behavior. One of the most interesting findings in the supplied recent corpus is that some biomasses improve the ash chemistry of difficult coals. Putra et al. [9] examined Calliandra calothyrsus and Gliricidia sepium in a high-sulfur, high-iron coal system and reported that biomass addition increased high-melting minerals, decreased Fe-based minerals, raised ash fusion behavior, and reduced deposition in drop-tube-furnace tests. That outcome is highly significant because it shows that biomass can sometimes function as an ash-modifying agent, not merely a renewable heat source. Yet the same study also demonstrated that 25 wt% Gliricidia could produce Ca2SO4-dominated behavior associated with strong adhesion and material degradation, meaning the benefit has a threshold beyond which the chemistry turns unfavorable [9]. This threshold logic is one of the most important conceptual advances in the updated literature.

Compatibility also extends beyond chemistry to mechanical and logistic behavior. Wang et al. [3] showed that direct cofiring in a full-scale 55 MW tangentially fired furnace was feasible at biomass shares below 20%, but higher percentages compromised furnace efficiency and challenged pulverizing performance because biomass particles were difficult to grind to the required fineness. Matveeva et al. [24] added a complementary perspective by demonstrating that co-milling wood and coal can create composite powders with favorable ignition and flame-propagation characteristics compared with simple mixtures. In plant practice, moisture and heterogeneity are equally important. Hartanto et al. [20] and Hermawan and Nurahman [25] both show that blending accuracy, stock management, drying, and homogeneous mixing have major effects on derating, green electricity output, and reliability. Thus, a modern compatibility map should include at least four dimensions: chemical compatibility, thermal reactivity, mechanical processability, and logistics stability [3], [20], [24].

Pretreatment, co-milling, drying, and physical preparation of biomass-coal blends

A notable strength of the new corpus is that it highlights physical preparation as a serious determinant of cofiring performance rather than a minor operational detail. In practical deployments, failures often originate upstream of the furnace-in storage, size reduction, or blending-before they become visible as flame instability or derating [20], [25]. This insight is important because many academic analyses focus on ash, emissions, or thermodynamics after the fuel enters the combustor, whereas utilities often experience the transition to cofiring first through handling problems.

Drying is a basic but consequential example. Nigay et al. [26] estimated the energy consumption required to dry forest combustible materials before their use in boilers and showed that, at initial moisture contents of 50-70%, complete moisture removal can consume roughly 10-13% of the biomass calorific value. They also found that total drying time was relatively insensitive to biomass type under identical conditions, which suggests that drying system design can often be standardized more easily than ash behavior can be generalized [26]. Hartanto et al. [20] translate this type of insight to plant practice by showing that trapezoidal stacking for natural drying and segregation of sawdust stocks materially reduced derating in a 2 × 315 MW coal-fired power plant. In other words, moisture management is not a secondary housekeeping concern; it is a core performance variable in cofiring.

Co-milling is another important preparation pathway. Matveeva et al. [24] showed that co-milling coal and wood does not simply reduce particle size independently; it can create composite powders in which coal covers wood particles, changing ignition and mass-loss behavior. The resulting composites shortened ignition delay and lowered the limiting concentration required for flame propagation, effectively shifting the combustion response of the mixture relative to a simple blend [24]. When read together with Syrodoy et al. [11], who found that stable ignition of large wood particles can be enabled by the presence of fine coal particles and that ignition delay depends on ambient temperature and composition, the literature suggests that the structure of the prepared blend matters as much as nominal composition. This is a major implication for industrial blending strategies because it suggests that blend preparation is an active means of controlling reactivity, not merely a passive mixing step [11], [24].

Pretreatment through carbonization or torrefaction has also gained renewed relevance. Ashizawa et al. [6] found that carbonized wood pellets with a fixed-carbon content around 25 wt.% could provide lower CO2 emissions per calorific value than ordinary wood pellets in the Japan-focused case studied, while maintaining attractive economics even at higher cofiring ratios. This suggests that pretreatment can improve not only storage and transport characteristics but also system-level economics. At a more mechanistic level, Richa et al. [27] showed that potassium can catalyze biomass thermal degradation and promote char formation during torrefaction and pyrolysis, indicating that intrinsic mineral matter strongly shapes the outcome of thermal pretreatment. These findings matter for cofiring because pretreatment changes grindability, reactivity, volatile release, and ash chemistry simultaneously [6], [27]. The updated literature therefore supports viewing pretreatment as part of the fuel-design problem rather than as a separate biomass-processing topic.

The practical implication is that biomass qualification should include a physical-preparation workflow alongside chemical screening. A feedstock that is chemically acceptable but persistently wet, hygroscopic, or difficult to mill may produce enough handling-induced variability to undermine the benefits predicted by laboratory combustion tests [3], [20]. Conversely, a marginal feedstock may become operationally viable with improved drying, co-milling, carbonization, or digital stock management [6], [25]. This middle-ground perspective is important because it moves the debate beyond a simple binary of “suitable” versus "unsuitable" biomass and toward the more useful question of what interventions are needed to convert an available biomass into a controllable cofiring fuel.

Combustion characteristics, ignition, burnout, and furnace-level behavior

The combustion literature in the supplied corpus shows that biomass cofiring can improve several furnace outcomes, but those gains are conditional on fuel composition, burner configuration, and operating mode. One recurring benefit is improved ignition or faster flame response when a reactive biomass fraction is blended with coal [11], [24]. Syrodoy et al. [11] experimentally studied free-falling wood-coal particle mixtures under radiation-convective heating and found that ignition delay decreased as the concentration of fine coal particles increased at relatively low temperatures. Importantly, they also observed that stable ignition of relatively large wood particles could still be achieved when mixed with fine coal. This result supports the practical feasibility of mixed-fuel ignition in real boiler environments, while also emphasizing that particle-size relationships are crucial [11].

At the drop-tube scale, cofiring often improves burnout and selected gaseous emissions. Ashraf et al. [28] compared coal with several agricultural residues and found that adding biomass lowered NOx, SO2, and CO emissions while increasing carbon burnout across all blends studied. The magnitude of the benefit depended on the type of agricultural residue: rice husk excelled in SO2 reduction, whereas corn husk produced strong CO reduction and high burnout [28]. A similar direction of effect is visible in Wang et al. [3], where biomass direct cofiring in a full-scale pulverized coal furnace significantly reduced NOx and also improved the performance of SNCR, although biomass shares above 20% sharply affected furnace efficiency and pulverizing performance. Together, these findings suggest that biomass can improve combustion chemistry and emission profiles while still imposing upper-bound constraints driven by thermal efficiency and handling limitations [3], [28].

The updated literature also clarifies the importance of aerodynamics and staging. Le and Nguyen [17] used CFD in a pilot-scale pulverized coal-fired furnace and showed that the rotation angle of the swirl generator strongly affected flame shape. A 10° angle was selected because it minimized SO2 formation and prevented direct contact between the flame and the upper furnace wall. When biomass ratios of 10-30% were simulated, the SO2 and NO mass fractions at the outlet dropped substantially, demonstrating the emissions promise of cofiring under tuned conditions [17]. This is a critical point: emissions benefits are not guaranteed by biomass presence alone; they are realized through burner and furnace conditions that preserve stable and well-positioned combustion. The literature therefore points toward an integrated approach in which fuel choice and aerodynamics are optimized together rather than sequentially.

Alternative combustion regimes provide further evidence that operating mode can expand the cofiring performance envelope. Hu et al. [29] showed that MILD combustion of a sawdust-coal blend reduced fuel-NO by at least 45.5% and PM2.5 by more than 37%, while maintaining burnout rates above 95%. The study suggests that low-temperature preheated-air MILD operation can suppress pollutant formation and fine-particle emissions without sacrificing burnout [29]. This is especially relevant for cofiring because mixed fuels often challenge conventional flame structures. MILD combustion effectively reframes the problem: rather than asking only whether a biomass is compatible with an existing flame, it asks whether the combustion mode can be adapted to make a wider range of biomass blends usable [17], [29]. Such findings point to the importance of viewing cofiring as a furnace-design and control problem rather than a static fuel-substitution exercise.

Oxy-fuel and pressurized operation: expanding the technology envelope

Although most practical discussions of cofiring still center on conventional air-fired pulverized coal boilers, the extracted literature also demonstrates a significant stream of work on oxy-fuel and pressurized fluidized-bed systems. This is important because it connects cofiring not only to near-term renewable substitution but also to carbon capture pathways and future decarbonization platforms [16], [30]-[31]. The oxy-fuel literature suggests that coal-biomass mixtures can be combusted stably while generating flue gases with higher CO2 concentration, improving readiness for capture.

Liu et al. [16] investigated pollutant emissions during cofiring of coal and biomass waste fuels in a 10 kWth oxy-fuel fluidized bed. They showed that increasing the biomass blending ratio generally increased CO and CH4 but reduced NO and NOx because of fuel-nitrogen dilution and enhanced reduction reactions; SO2 also decreased as biomass ratio and Ca/S and K2/S molar ratios increased [16]. The study is valuable because it demonstrates that pollutant responses under oxy-fuel cofiring are multi-dimensional and mediated by both fuel properties and excess oxygen ratio. Liu et al. [30] extended this line by demonstrating stable combustion and rapid state switching in a continuous-feed oxy-fuel fluidized bed, with optimal biomass ratios depending on fuel type and combustion mode. Stable combustion was maintained when inlet oxygen concentration reached 30% or more, and the best biomass windows produced more uniform temperatures, increased CO2 generation, and lower unburnt carbon [30].

Pressurized oxy-fuel cofiring goes one step further. Liu et al. [31] tested coal-biomass cofiring in a 10 kWth pressurized fluidized bed and found that increasing both pressure and biomass ratio improved temperature distribution, CO2 enrichment, and combustion efficiency while reducing NOx and SO2 emissions by more than 30%. The stable realization of a pressurized oxy-fuel mode is especially relevant because it combines cofiring with low-cost carbon-capture potential, albeit in a less mature configuration than conventional air-firing [31]. While these studies remain at pilot scale, their collective implication is important for review purposes: the technology space of coal-biomass cofiring is broader than conventional direct substitution in utility boilers. The field is increasingly intersecting with carbon-capture strategies and future low-carbon thermal systems [31]-[32].

This line of research also affects how today's direct-cofiring studies should be interpreted. If air-fired direct cofiring is treated only as a temporary decarbonization measure, some of its technical constraints may seem like limits to the whole field. But if it is interpreted as one branch of a wider thermochemical transition pathway-one that also includes oxy-fuel fluidized beds, pressurized systems, gasification, and eventually BECCS-like configurations-then the significance of current compatibility, ash, and optimization work becomes even greater [32]-[34]. The near-term and long-term branches of the literature are therefore more connected than they first appear.

Ash chemistry as the core technical boundary: slagging, fouling, deposition, and phase transformation

Among all topics in the updated corpus, ash chemistry most consistently determines whether cofiring remains beneficial or becomes operationally costly. This is why ash-related studies now sit at the center of the field rather than at its margins [8], [10], [23]. The recent literature does not rely on a single predictive method. Instead, it increasingly combines theoretical prediction, ash indices, ash fusion temperatures, XRD, XRF, SEM-EDS, probe observations, and furnace tests to build a layered understanding of deposition behavior [9], [13], [21]. This methodological pluralism is a sign of maturation because no single ash index can adequately capture low-melting phase formation, sintering, or adhesion across the wide range of biomass-coal systems now being studied.

Hariana et al. [8] provide a strong example of integrated ash evaluation. In their study of coal blended with a mixture of empty fruit bunch and palm frond, a 25% biomass share gave the best combustion performance but also increased slagging risk due to lower ash fusion temperatures, sticky probe deposits, and mineralogical evidence of more problematic ash behavior. This is a crucial finding because it shows that combustion performance and ash safety do not necessarily align [8]. A blend may burn well and still be unsuitable because of deposit formation. That tension recurs throughout the corpus and is one reason why the field increasingly emphasizes bounded operating windows rather than maximum substitution targets.

The palm-waste follow-up study by Hariana et al. [12] deepens this picture. Experimental investigation of ash deposits during cofiring with palm residues confirmed that 25% biomass addition altered ash properties and intensified slagging, while a mixed biomass composition outperformed single residues from the slagging perspective. The implication is that biomass-biomass blending can sometimes be used to rebalance ash chemistry within a cofiring system [12]. This is a strategically important point because it suggests that the choice is not merely between coal and one biomass; rather, multiple biomass streams can be combined to create a more compatible composite fuel. Darmawan et al. [23] reinforce this broader view by discussing a staged ash-evaluation workflow for palm residues, rice husk, solid recovered fuel, and mixed hardwood chips, followed by the possible use of additives to improve ash behavior.

The RDF and waste-fuel literature makes the consequences of poor ash chemistry especially clear. Novendianto et al. [13] investigated organic refuse-derived fuel blended with coal at 5-20 wt% and found that chlorine content increased sharply with RDF proportion. Up to 10 wt%, the blends showed relatively clean probe observations, low gas emissions, and no sintering, indicating manageable ash behavior. At 15 wt%, early warning signs of slagging and fouling appeared, and at 20 wt% the probes clearly indicated serious ash-related problems [13]. This study is exceptionally useful for decision-making because it demonstrates a quantifiable transition from acceptable to unacceptable performance as biomass share increases. It therefore supports the general idea that blend windows should be empirically bounded and should not be set by policy targets alone [13], [23].

Chen et al. [21] provide another compelling case, this time with eucalyptus bark and several coals. Their XRD, XRF, SEM, and E-TOPSIS analysis showed that eucalyptus bark increased particle size, sintering, and adhesion and promoted the formation of muscovite, anorthite, and calcite-related ash structures. The result was severe slagging tendency in multiple combinations [21]. The lesson is broader than the specific biomass: even a plentiful or low-cost residue can be a poor cofiring fuel if it drives the ash system toward low-melting or highly adherent phases. This finding also underscores why “renewable availability” is not a sufficient engineering criterion. In practical plant terms, a low-cost biomass that increases outages, cleaning burden, or tube degradation is not a low-cost fuel at all [4], [21].

The most constructive ash result in the supplied literature comes from Putra et al. [9], who showed that Calliandra and Gliricidia could improve the ash characteristics of a problematic high-sulfur, high-iron coal by increasing high-melting minerals and reducing Fe-rich phases. Yet the study also found that excessive Gliricidia introduced $Ca2SO4$-dominated behavior with strong adhesion and material degradation risk. This dual outcome is conceptually important because it demonstrates both the possibility of chemical improvement and the reality of threshold reversal [9]. The updated literature therefore supports a new rule for ash-related decision-making: biomass approval must be pair-specific, ratio-specific, and phase-aware. Generic ash indices remain useful for screening, but implementation-quality decisions require integrated mineralogical and experimental validation [8], [10], [23].

Corrosion and materials selection: from downstream maintenance issue to front-end design constraint

Corrosion is one of the clearest examples of a topic that has moved from the periphery of cofiring discourse toward the center. Earlier transition narratives often emphasized emissions reduction and renewable substitution while treating materials degradation as an operational afterthought. The extracted recent literature does not permit that simplification [15], [35]. Biomass introduces chlorine and alkali species that can strongly affect deposit chemistry and accelerate fireside corrosion, which in turn influences tube life, maintenance schedules, outage risk, and long-run cost [13], [15], [36].

Nugraha et al. [35] frame the issue from a materials perspective by comparing steel and stainless-steel boiler tubes in cofiring environments and highlighting fireside corrosion as a major concern for heat-exchanger components. Although the study is perspective-oriented, it underscores a crucial point: cofiring cannot be judged solely on fuel and furnace performance; material compatibility is part of the technology's viability. Syaadah et al. [15] provide the strongest direct evidence through embedded corrosion tests using fly ash from stoker, pulverized-coal, and circulating-fluidized-bed systems with 2-5% biomass addition. They found that stoker fly ash produced higher corrosion mass gain than PC and CFB ash, and that increasing biomass content increased corrosion products, with 5 wt.% biomass giving the highest mass gain. SEM-EDS and XRD detected Fe2O3 and FeCl2 on the sample surfaces, implicating chlorine and alkali chlorides in accelerated degradation [15].

When read together with the ash literature, corrosion appears as the materials endpoint of deposit chemistry. For example, organic RDF raises total chlorine in coal blends and becomes problematic at higher substitution ratios [13]. Palm residues and some woody biomasses can promote sticky or low-melting deposits that are more likely to maintain aggressive surface environments on boiler tubes [10], [12]. Putra et al. [9] explicitly mention material degradation risk under sulfate-dominated adhered ash in higher-Gliricidia blends. Thus, corrosion cannot be fully understood or mitigated if evaluated separately from deposition, fouling, and ash mineral transformation. The literature strongly suggests that tube degradation is not an isolated maintenance topic but an emergent property of the ash system as a whole [9], [13], [15].

This has practical consequences for plant deployment. First, blend ratios should be bounded not only by emissions or efficiency targets but also by corrosion onset and deposit aggressiveness [3], [15]. Second, biomass streams with high chlorine or alkali content should trigger more conservative approval protocols, especially in units with vulnerable tube materials or prior deposition problems [13], [35]. Third, materials selection and monitoring should be integrated into cofiring strategy from the outset rather than added after operational problems emerge. The literature does not yet provide a full long-term corrosion economy model, but it clearly signals that future top-tier work should connect corrosion rates, maintenance cost, outage probability, and fuel economics in one framework [4], [15].

Emissions, pollutant control, and the increasingly multi-objective nature of performance

One reason cofiring remains attractive despite its technical complexity is that many studies still report meaningful reductions in pollutant emissions and carbon intensity. The challenge, as the updated corpus shows, is that emissions benefits must be interpreted within a multi-objective setting in which efficiency, deposition, materials health, and cost are also changing [17], [19], [28]. It is therefore misleading to evaluate cofiring only by stack-gas improvements.

Conventional air-fired studies generally support beneficial trends for NOx and SO2. Ashraf et al. [28] found lower NOx and SO2 across agricultural-residue blends in a drop-tube furnace. Wang et al. [3] observed significant NOx reduction in a full-scale tangentially fired furnace with biomass direct cofiring and improved SNCR response. Le and Nguyen [17] reported CFD-predicted reductions in SO2 and NO of approximately 1.4 to 4 times at the outlet of a pilot-scale furnace as biomass ratio increased from 10% to 30%, provided the swirl setting was appropriate. Suyatno et al. [10] similarly reported potential flue-gas reductions of 30-60% for woody-biomass blends, though with moderate risk levels that discouraged simplistic interpretation. The recurrent pattern is clear: emissions can improve meaningfully, but those benefits depend on both fuel and combustion condition [10], [17], [28].

Oxy-fuel and pressurized studies add further nuance. Under oxy-fuel fluidized-bed conditions, increasing biomass generally lowers NOx and SO2 but can increase CO or CH4 depending on operating conditions and excess oxygen ratio [16]. In pressurized oxy-fuel mode, higher pressure and biomass blending can improve combustion efficiency and reduce NOx and SO2 by over 30% while enriching CO2 in the flue gas, which is advantageous for capture [31]. These studies show that emissions optimization is not merely a function of biomass fraction but of operating mode, oxygen concentration, and reactor hydrodynamics [30]-[31]. This makes the performance problem inherently multi-objective and dynamic.

The same lesson appears at plant scale. Efendy et al. [19] framed boiler operation under biomass cofiring as a dynamic and nonlinear problem in which efficiency, CO2 emissions, and capability factor interact. Their recurrent-neural-network and multi-objective genetic algorithm approach improved boiler efficiency, reduced CO2 emissions, and increased capability factor more effectively than response-surface methodology. This study is important because it shows that cofiring does not merely introduce a new fuel; it changes the structure of the control problem [19]. When mixed-fuel combustion is variable, the optimal operating point is no longer static. Digital optimization becomes necessary not because it is fashionable, but because the physical system is more complex.

This multi-objective framing should alter how future review articles and plant trials define success. An emissions-only improvement can be operationally unattractive if it is accompanied by derating, higher cleaning frequency, or severe ash-related risk. Conversely, a modest biomass share that yields stable combustion, manageable ash chemistry, and lower emissions may be strategically superior to an aggressive share that maximizes renewable fraction on paper but degrades reliability [4], [19]-[20]. The current literature thus supports composite decision metrics rather than single-point performance claims.

Digitalization, monitoring, and optimization: the rise of data-rich cofiring

The integration of digital tools is one of the most distinctive features of the recent evidence base. The older logic of cofiring was mainly static: select a blend, run the unit, compare emissions or ash behavior, and report feasibility. The newer logic is adaptive and data-rich. Digital blending tools, image-based combustion-state recognition, and machine-learning optimization are all now appearing in the supplied studies [19], [25], [37]. This trend is especially important because mixed-fuel systems are intrinsically variable in moisture, particle size, volatile release, and ash chemistry.

At the fuel-handling level, Hermawan and Nurahman [25] describe advanced coal-biomass blending and digitalized stock management at Pelabuhan Ratu Coal-Fired Power Plant. They report increased biomass utilization, higher green-energy production, improved blending accuracy, and a substantial reduction in potential derating losses due to low calorific value. This study is operationally important because it makes clear that data systems and operator guidance can improve cofiring quality before the fuel even reaches the burner [25]. Hartanto et al. [20] provide a complementary case in which structured mixing and RIOT-based monitoring reduced monthly derating events and increased green electricity generation. These cases collectively show that the stockyard and blending zone are part of the digital combustion system boundary.

Inside the furnace, image-based and machine-learning methods are becoming more prominent. Kotyra [37] explored convolutional neural networks for identifying different biomass co-combustion states from flame-image sequences collected under varying fuel and airflow rates. The significance of this work lies in the latency and directness of flame images: they provide a near-real-time visual proxy for combustion stability and can potentially support supervisory control in mixed-fuel systems where conventional signals alone may respond too slowly or ambiguously [37]. Such work should not be dismissed as merely a signal-processing exercise. It responds to a genuine physical challenge: biomass cofiring can change flame texture and stability, making visual state recognition a practical control asset.

At the plant-optimization level, Efendy et al. [19] demonstrate the value of dynamic, multi-objective AI-based optimization. Their model improved boiler efficiency and capability factor while reducing CO2 emissions in a 660 MW supercritical unit. Importantly, the study treats cofiring variability as the reason optimization is needed, not as a side effect to be ignored. This point aligns well with Le and Nguyen's CFD study, which showed that even swirl angle significantly affects whether the mixed-fuel flame behaves advantageously or unfavorably [17], [19]. Digitalization in cofiring should therefore be understood as an engineering necessity emerging from variable mixed-fuel physics.

The broader implication is that cofiring research is moving toward hybrid intelligence: physically informed models for ash, combustion, and heat transfer combined with real-time sensing and machine-learning adaptation. Such hybrid systems are likely to be more robust than black-box optimization alone because they can incorporate ash-related constraints, corrosion risk, and blending limits directly into control logic [19], [23], [37]. This is one of the clearest areas where the supplied recent literature changes the substance of the field relative to older baseline reviews.

Plant implementation, reliability, economics, and logistics

The literature on plant implementation reminds us that technical feasibility at laboratory scale does not guarantee utility-scale success. In real plants, cofiring lives or dies through reliability, procurement, handling discipline, and cost control [1], [4], [20]. This is particularly visible in Indonesian case studies, which are strongly represented in the supplied corpus and are valuable because they move beyond theoretical potential into operational experience.

Arifin et al. [4] provide a techno-economic analysis of 5% biomass cofiring in pulverized-coal boilers in Indonesia. They found that co-firing impacts plant efficiency in relation to biomass heating value, has little effect on furnace exit gas temperature, and can strongly reduce SO2 and NOx depending on biomass sulfur and nitrogen content. At the same time, generation cost increased because biomass energy was more expensive per unit of useful fuel energy than coal. Yet the annual production of green energy and carbon-credit potential remained significant [4]. This study is instructive because it shows that cofiring can be both technically attractive and cost-sensitive at the same time. Economic viability depends less on whether cofiring "works" than on how biomass price, fuel quality, and policy incentives are structured.

Saputra and Oktarina [38] extend the economic discussion by using mixed-integer linear programming to optimize biomass blending across several coal-fired power plants. Their model achieved simultaneous fuel-cost and CO2-emission reductions when blending was optimized subject to quality requirements, supply capacity, transport alternatives, and plant demand. This is a particularly useful result because it frames blending as a system-wide planning problem rather than a unit-by-unit experiment [38]. Ashizawa et al. [6] add an international trade and pretreatment dimension, showing that carbonized wood pellets produced overseas can be economically competitive and reduce CO2 intensity in Japanese coal plants. These studies collectively imply that economics must be evaluated at multiple scales: fuel property, plant operation, supply chain, and policy environment.

Reliability, however, is often the decisive factor in practice. Hartanto et al. [20] show that sawdust cofiring initially created uneven combustion, bunker plugging, coal-flow limits, and frequent derating in a utility plant, but that structured stock segregation, drying, and homogeneous mixing sharply reduced these problems. This case is one of the most practically valuable studies in the corpus because it identifies a low-cost intervention that changes the effective performance of biomass without requiring a major boiler retrofit. It reinforces the idea that fuel logistics and plant operations are inseparable from combustion success [20]. Hermawan and Nurahman [25] similarly show that digitalized fuel-stock management can increase blending accuracy and reduce derating risk, again demonstrating that reliability begins upstream.

These operational studies also highlight an important asymmetry in cofiring deployment: many of the largest benefits are unlocked not by radical new hardware but by disciplined management of moisture, stock geometry, blend homogeneity, and digital oversight [20], [25]. This insight is valuable for near-term transition strategy because such interventions are often faster and cheaper than major hardware modifications. At the same time, the studies remind us that policy or corporate mandates to increase biomass ratio too quickly can be counterproductive if logistics and handling systems are not ready [7], [20]. In short, the updated literature supports a deployment philosophy in which operational maturity must keep pace with substitution ambition.

Life-cycle assessment, environmental accounting, and broader sustainability boundaries

A major substantive update relative to older cofiring reviews is the growth of studies that evaluate impacts beyond direct stack emissions. The supplied recent literature includes life-cycle analyses, carbon-economy calculations, and broader sustainability discussions that complicate simple “biomass equals low carbon” assumptions [14], [18], [39]. This is an important advance because direct combustion benefits do not automatically translate into superior overall environmental outcomes once feedstock collection, transport, land use, or ash disposal are considered.

Febijanto et al. [18] provide one of the clearest examples. Using actual operational data from coal-firing and sawdust co-firing units in Banten, they found that cofiring reduced global warming potential, acidification potential, eutrophication potential, photochemical ozone formation potential, fossil abiotic depletion, and water scarcity. However, abiotic depletion of elements, ozone depletion potential, and especially land use increased, with land use becoming highly sensitive as the cofiring ratio rose from 11.8% to 20% [18]. This result is crucial because it shows that cofiring should not be evaluated by a single environmental headline. The same program can improve several impact categories while worsening others. Review articles that ignore these trade-offs risk overstating sustainability.

Vargas-Soplín et al. [14] enrich the systems perspective by comparing alternative uses of urban autumn leaves. In their Berlin case, cofiring in existing power plants achieved the highest net present value and the lowest net greenhouse-gas emissions compared with gasification, biogas production, and composting. This result suggests that cofiring can be highly attractive when a problematic waste stream is locally available and existing thermal infrastructure can absorb it efficiently [14]. Yet the study also notes strong sensitivity to leaf dryness and electricity tariffs, emphasizing again that logistical and economic context shapes environmental outcomes.

The literature on negative-emission pathways and engineering thermochemistry helps place cofiring in a broader decarbonization framework. Han et al. [33] argue that thermochemical industries are central to carbon-neutrality challenges and that engineering thermochemistry provides a framework for reducing emissions from super-emitters. Cheng et al. [32] evaluate life-cycle optimization of negative-emission technologies in electricity generation and show that cost and net-CO2 objectives can favor different configurations. Although these studies do not focus exclusively on biomass cofiring, they are valuable to this review because they situate cofiring within a larger family of thermochemical transition strategies rather than as an isolated intervention [32]-[33]. In this framing, direct cofiring is one pathway among several possible bridge strategies linking current coal assets to lower-carbon futures.

Ash valorization further expands the sustainability boundary. Das et al. [39] review mechanochemical synthesis of coal combustion residual ash composites for construction materials and show that coal-derived ash streams can be transformed into useful materials with improved environmental performance. For cofiring, this matters because ash should increasingly be seen as both a boiler risk and a downstream resource stream. If the ash can be better managed and beneficially utilized, then the overall sustainability profile of cofiring improves beyond combustion alone [39]. The recent literature does not yet integrate cofiring ash management with full downstream valorization in a single framework, but it clearly points in that direction.

MATERIALS & METHODS

This study adopts a narrative literature review approach focused on coal-biomass cofiring studies published between 2018 and 2026. The evidence base covers feedstock characterization, ash behavior, combustion performance, corrosion, digital optimization, techno-economic analysis, and environmental assessment, thereby combining laboratory, pilot-scale, plant-scale, modeling, and systems studies [1], [6], [9], [36].

The synthesis was organized using a decision-oriented framework rather than a purely chronological one. The reviewed studies were grouped according to the main engineering decisions that determine cofiring success: feedstock approval, blend-ratio selection, pretreatment and co-milling, ash and deposit risk, corrosion and materials, burner and furnace tuning, operational reliability, and broader sustainability evaluation [6], [20], [25], [38].

Comparative synthesis was then used to identify recurring benefits, failure thresholds, and emerging design principles across the literature. Three summary tables were prepared to map the evidence base, compare the main benefits and technical risks, and translate the reviewed findings into a practical deployment framework.

RESULT

Across the reviewed literature, five recurring result patterns are evident. First, cofiring performance is governed by compatibility between specific biomass-coal pairs rather than by broad feedstock labels. Second, technically acceptable blend windows are bounded by ash behavior, corrosion onset, milling performance, and efficiency response. Third, physical preparation - drying, co-milling, carbonization, and stockyard control - materially affects plant operability. Fourth, digital monitoring and optimization increasingly improve combustion stability and reduce derating. Fifth, broader life-cycle and techno-economic outcomes remain strongly context dependent [3], [9]-[10], [13], [15], [20]-[21], [25], [31].

Table 1 summarizes the major studies included in this review and identifies the main contribution made by each one. Table 2 compares the main operational benefits and technical penalties reported across representative biomass streams and cofiring interventions.

Table 1. Overview of the updated evidence base and its primary contribution to contemporary coal-biomass cofiring understanding.

Study domain	Fuel or system context	Methods / scale	Core finding	Implication for review	Ref.
Baseline framing	General coal-biomass cofiring	Review / book chapter	Cofiring is practical in existing assets but constrained by fuel supply, characterization, and policy support	Sets the transition rationale but also identifies enduring system constraints	[1]
Feedstock review	Palm-oil residues with coal	Comparative review	Palm-oil wastes have strong cofiring potential but require careful characterization before implementation	Abundance does not remove the need for feedstock qualification	[2], [22]
Full-scale direct cofiring	55 MW tangentially fired PC furnace	Industrial furnace test	<20% biomass was feasible and reduced NOx, but higher shares challenged efficiency and pulverizing	Practical blend ceilings are often set by grinding and furnace performance	[3]
Combustion / emissions	Coal with agricultural residues	Drop-tube furnace	Biomass lowered NOx, SO2, and CO while improving burnout, depending on residue type	Emission gains are feedstock-specific, not generic	[28]
Ash evaluation	Palm residues with coal	Indices, TG-DSC, DTF, SEM-EDX, XRD	25% biomass improved combustion performance but increased slagging tendency	Combustion and ash safety do not necessarily align	[8]
Ash improvement	Calliandra / Gliricidia with difficult coal	FactSage + DTF + ash analysis	Biomass improved ash behavior by increasing high-melting minerals, but higher Gliricidia triggered sulfate-rich adhesion	Compatibility is ratio-dependent and can reverse beyond a threshold	[9]
Ash hazard	Eucalyptus bark with four coals	SEM, XRF, XRD, E-TOPSIS	Eucalyptus bark intensified sintering, adhesion, and severe slagging in several combinations	Low-cost biomass can still be technically unacceptable	[21]
Chlorine-rich waste fuel	Organic RDF with coal	Empirical indices + DTF + SEM-EDS + XRD	Up to 10 wt% was manageable, while 15-20 wt% created clear ash-related problems	Blend windows should be bounded experimentally, not assumed	[13]
Woody biomass screening	Acacia and mahogany with coal	Lab combustion + SEM-EDS + XRD + gas analysis	Acacia produced cleaner ash than mahogany; mahogany formed low-melting phases	Species-level screening is essential within woody biomass classes	[10]

Plant implementation	Sawdust cofiring in 2 × 315 MW unit	Plant operation + RIOT monitoring	Structured drying and blending reduced derating and increased green electricity	Fuel logistics are part of the combustion system boundary	[20]
Digital optimization	660 MW supercritical boiler	RNN + RSM + MOGA	AI-based optimization improved efficiency, CO2 emissions, and capability factor	Mixed-fuel operation is a dynamic optimization problem	[19]

Table 2. Comparative patterns in benefits, penalties, and operational lessons across the reviewed literature.

Biomass / intervention	**Main benefit reported**	**Main technical risk**	**Evidence base**	**Operational lesson**	**Ref.**
Palm-oil wastes	Abundant local feedstock; potential reductions in GHG, NOx, and Sox	Ash-related issues if chemistry is unmanaged	Comparative review + experimental ash studies	Supply potential must be converted into chemistry-aware qualification	[2], [12], [22]
Agricultural residues	Lower NOx, SO2, and CO; improved burnout	Performance depends on residue type and blend ratio	Drop-tube combustion	Residue-specific selection matters for emissions strategy	[28]
Carbonized wood pellets	Potentially favorable CO2 and economic performance at higher ratios	Requires pretreatment infrastructure and supply-chain design	Systems analysis	Pretreatment can improve viability, not just fuel quality	[6]
Co-milling of wood and coal	Shorter ignition delay and improved flame propagation	Requires process control and appropriate milling strategy	Particle-scale experiments and TGA	Blend preparation changes combustion behavior materially	[24]
Calliandra / Gliricidia	Reduced Fe-rich ash and higher-melting minerals	Excess Gliricidia promoted Ca2SO4-rich adhesion and material degradation	Modelling + DTF + ash characterization	Benefits can reverse beyond a chemistry threshold	[9]
Eucalyptus bark	Potential biomass resource	Severe slagging, sintering, adhesion	SEM, XRF, XRD, E-TOPSIS	Do not scale a biomass without compatibility proof	[21]
Organic RDF	Diversion of organic waste to energy	High chlorine drives slagging, fouling, and corrosion above safe windows	Indices + DTF + SEM-EDS + XRD	Waste-derived fuels need stricter threshold management	[13]
MILD combustion	Large reductions in fuel-NO and PM2.5 with high burnout	Requires modified combustion mode	Pilot-scale furnace tests	Combustion regime can enlarge the feasible biomass envelope	[29]
Stockyard drying and structured mixing	Lower derating and higher green electricity	Moisture and segregation remain critical without discipline	Plant-scale implementation	Reliable cofiring begins in storage and blending	[20], [25]
Embedded corrosion testing	Direct evidence of chlorine-accelerated material degradation	Tube-life penalties even at low biomass ratios	Corrosion exposure + SEM-EDS + XRD	Corrosion must be treated as a front-end design constraint	[15]

DISCUSSION

Comparative synthesis and emerging design principles

When the supplied literature is read as a whole, several design principles emerge that were less visible in earlier reviews. The first is compatibility over generic availability. Biomass should not be approved because it is abundant or renewable in principle, but because it remains compatible with a specific coal and plant system across chemistry, reactivity, handling, and materials constraints [9], [20]-[21]. This means that future fuel qualification protocols should be explicitly pairwise and should include mineralogy, ash-fusion behavior, chlorine and alkali content, grindability, and moisture response [2], [8], [10].

The second principle is bounded blend-window design. Many studies in the extracted corpus show a threshold beyond which benefits reverse. Organic RDF can be relatively safe up to about 10 wt.% and then become increasingly problematic [13]. Eucalyptus bark worsens slagging in several combinations [21]. Gliricidia can improve ash characteristics at some levels yet produce sulfate-dominated adhered ash at higher ratios [9]. Full-scale furnace studies show practical limits around 20% under direct cofiring because of efficiency and milling problems [3]. The key lesson is that blend ratio should not be treated as a simple scalar target. It is a bounded operating variable whose safe range must be demonstrated experimentally and operationally [13], [15].

The third principle is that ash and corrosion form the hard technical boundary of implementation. Emissions and decarbonization benefits are valuable, but they are not the decisive engineering constraint if deposits and tube degradation rise sharply [12], [15]. This is why the most credible recent cofiring studies increasingly combine theoretical prediction with experimental validation and post-combustion characterization [10], [23]. A top-tier future research standard will likely require integrated ash-risk, deposit, and corrosion evaluation rather than standalone combustion or emission measurements.

The fourth principle is that operational intelligence can materially enlarge the feasible performance envelope. Structured blending, natural drying, digital stock management, flame-image classification, CFD-based burner tuning, and RNN-based multi-objective optimization all demonstrate that mixed-fuel systems can be actively controlled rather than passively tolerated [17], [19], [25], [37]. This is a major shift in the substance of the field. It means that cofiring should be researched not only as a fuel property problem but as a cyber-physical plant problem in which sensors, models, and operators jointly determine outcomes.

The fifth principle is that sustainability assessment must widen its boundaries. The recent literature consistently warns against reading cofiring through a single metric such as direct CO2 reduction. Techno-economic studies show sensitivity to biomass pricing and carbon incentives; life-cycle studies show trade-offs across environmental impact categories; and ash-valorization work suggests downstream benefits that conventional emissions studies miss [4], [18], [39]. Therefore, next-generation review work and plant planning should use integrated metrics that combine emissions, cost, reliability, materials impact, and resource efficiency.

Research agenda for the next phase of coal-biomass cofiring

The extracted literature supports a clear agenda for future research and deployment. First, the field needs compatibility atlases that map biomass-coal pairs rather than single fuels in isolation. Such atlases should include ash indices, thermodynamic modeling, ash fusion temperatures, probe results, and where possible short-duration corrosion screening. The aim should be to identify not just good or bad biomasses, but blend windows and failure thresholds [9]-[10], [23]. Without this, utilities will continue to overgeneralize from one promising residue or one successful case study.

Second, more research is needed on preparation pathways such as drying, co-milling, carbonization, and digital stock management. The existing studies already show that handling and physical preparation can determine whether a chemically attractive biomass becomes operationally stable [20], [24], [26]. Yet the literature remains fragmented, with thermal behavior, particle structure, and yard logistics often studied separately. Integrated studies that connect moisture control, particle morphology, combustion response, and ash behavior would be particularly valuable.

Third, long-duration corrosion and deposit studies remain a major need. Short or laboratory-scale investigations have already identified chloride-related acceleration and deposit-threshold effects, but the field still lacks enough work linking exposure duration, maintenance burden, and economic consequence [15], [35]. Future studies should combine embedded corrosion tests, deposit chemistry, and plant data on tube wear, cleaning intervals, and outages. This would make the materials literature more directly usable by utilities.

Fourth, digital and data-driven work should become more physically grounded. Machine-learning and imaging studies are promising, but their greatest value will come when they incorporate ash, corrosion, and fuel-quality constraints into supervisory control rather than optimizing only near-term emissions or efficiency [19], [37]. A physically informed digital twin for cofiring-linking fuel stock properties, blending states, burner settings, flame images, emissions, and ash-risk proxies-would represent a major step forward for the field.

Fifth, broader system-level analyses should continue. More life-cycle and techno-economic studies based on real plant data are needed, especially in regions that are scaling biomass cofiring under policy pressure [4], [7], [18]. Such work should assess not only direct emission reductions but also land use, biomass transport, feedstock seasonality, carbon pricing, and potential ash reuse. This is especially important because the strategic value of cofiring depends heavily on regional infrastructure, biomass supply patterns, and policy design [6], [14].

Finally, the literature suggests a need for more standardized reporting. Many studies report fuel types, blend ratios, and some ash or emission results, but fewer provide a fully comparable set of information on coal class, biomass pretreatment, moisture, particle size, ash mineralogy, operating conditions, and post-test deposit characteristics. A stronger reporting culture would substantially improve cross-study synthesis and allow the field to move faster from isolated success stories to generalizable engineering rules [1], [8], [23].

Table 3. Proposed decision framework for next-generation cofiring research and deployment.

Decision domain	**Key question**	**Evidence required**	**Preferred method mix**	**Decision criterion**	**Ref.**
Fuel qualification	Is the biomass-coal pair chemically and operationally compatible?	Mineralogy, chlorine/alkali context, moisture, grindability, ash-fusion behavior	Indices + ash fusion + SEM-EDS/XRD + handling tests	Approve only pair-specific compatible fuels	[2], [8], [21]
Blend-window definition	What biomass ratio remains beneficial and safe?	Deposition threshold, efficiency response, corrosion onset	Stepwise DTF / furnace tests + probe analysis + corrosion screening	Use bounded operating windows rather than fixed policy ratios	[3], [9], [13]
Physical preparation	Can drying, co-milling, or carbonization improve operability?	Moisture behavior, ignition delay, particle structure, logistics response	Drying tests + ignition experiments + co-milling /	Treat preparation as fuel design, not preprocessing only	[6], [24], [26]

			pretreatment trials		
Furnace tuning	Which combustion mode and burner settings stabilize mixed-fuel flames?	Flame shape, pollutant formation, wall interaction, burnout	CFD + pilot / full-scale furnace tests + flame imaging	Biomass benefits must be realized through tuned aerodynamics	[17], [29], [37]
Operational reliability	Can storage, drying, and mixing sustain homogeneous feed quality?	Moisture, segregation, plugging tendency, derating frequency	Stockyard monitoring + plant performance data	Fuel logistics are part of plant-level cofiring design	[20], [25]
Sustainability assessment	Does the project remain favorable beyond stack emissions?	Life-cycle impacts, generation cost, carbon savings, land-use effects, ash reuse options	LCA + techno-economic analysis + circular-economy assessment	Judge cofiring with integrated sustainability metrics	[4], [18], [39]

CONCLUSION

The updated evidence base shows that coal-biomass cofiring has matured into a more exacting and more interesting engineering field than earlier feasibility narratives implied. The central challenge is no longer simply to replace a portion of coal with renewable matter. It is to identify compatible fuel pairs, define safe blend windows, manage ash and corrosion, control furnace dynamics, stabilize logistics, and assess sustainability with system-wide boundaries [9], [18], [20]. This is a fundamentally different framing from the early low-risk substitution narrative, and it reflects the increasing technical maturity of the literature.

The reviewed studies collectively support three robust conclusions. First, biomass cannot be treated as a generic category: species, residue type, and pretreatment strongly affect ignition, milling, ash transformation, and deposit behavior [2], [10], [21]. Second, ash-related behavior remains the decisive technical filter for practical implementation because it mediates slagging, fouling, and corrosion risk across scales [12]-[13], [15]. Third, operational and digital intelligence is becoming essential for reliable mixed-fuel operation, with blending systems, image-based monitoring, and multi-objective optimization all contributing meaningfully to performance [19], [25], [37]. Under favorable compatibility and control conditions, cofiring remains a credible transitional decarbonization strategy for existing coal fleets. It can reduce selected pollutant emissions, produce green electricity, lower fossil dependence, and, in some contexts, deliver attractive economics or life-cycle benefits [4], [14], [20]. Under poor compatibility or weak operational discipline, however, the same intervention can generate serious ash-related problems, corrosion, derating, and hidden environmental trade-offs [13], [18], [21]. The next phase of the field should therefore be built on compatibility-based fuel qualification, bounded blend-ratio design, ash- and corrosion-aware control, and broader sustainability accounting. In that form, coal-biomass cofiring can remain technically relevant and strategically useful as part of a wider thermochemical transition toward lower-carbon energy systems [32]-[33], [39].

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