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Systematic Review

Environmental, Health and Socioeconomic Impacts of Wood-Based Fuels: A Systematic Review

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Abstract

The use of wood-based fuels remains a contested renewable energy option because, although it may contribute to fossil fuel substitution, its sustainability depends on the full supply chain, and it is often associated with environmental and air quality problems. This systematic review examines the environmental, health, and socioeconomic impacts of fuelwood use across the supply chain, including carbon cycle implications, poverty-related problems, and energy transition pathways. The review included 101 publications identified through a search of the Web of Science Core Collection and supplementary manual searching. PRISMA 2020 guided the reporting of the review. Reported impacts were strongly context dependent. Fuelwood use may support climate change mitigation, renewable energy goals, and energy diversification, but it may also contribute to forest disturbance, biodiversity loss, air pollution, health risks, and on-site carbon stock losses. Carbon benefits were conditional on sustainable biomass sourcing, maintained forest regrowth, efficient combustion, limited supply chain emissions, and avoidance of competition with long-lived wood product uses. Poverty and obsolete heating technologies were key factors reinforcing inefficient combustion, damp fuel use, high fuel demand, waste burning, illegal logging, and household air pollution. The reviewed evidence suggests that energy transition should not be understood only as a linear shift away from fuelwood. Instead, the main recommendation is the modernization of fuelwood systems through sustainable sourcing, short supply chains, dry and good-quality fuel, modern appliances, improved combustion control, and better-insulated buildings.

Keywords: wood energy; sustainable biomass; household air pollution; carbon cycle; energy transition

Academic Editor: Francesco Patuzzi

Received: 15 October 2026
Revised: 6 November 2026
Accepted: 23 November 2026
Published: 27 November 2026

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1. Introduction

Opinions on fuelwood use are divided, as there are conflicting arguments regarding its environmental [1,2] and social impacts and circumstances [3]. In a separate study [4], we already revealed that opinions about a complex environmental topic such as the impact of firewood use are mostly based on worries and other feelings about the environment in general. Limited access to reliable information may constrain informed public evaluation of the issue [4].

This is largely due to the fact that urbanization leads to a gradual disconnection from nature and the use of natural resources [5]. On the one hand, the growing distance generates disaffection toward nature [6]; on the other hand, it results in a distorted perception

of nature and natural resource use in which judgment on human impact on nature is polarized: nature untouched and nature ruined by humans. Pristine nature is idealized [7], disregarding its potential negative effects that need to be regulated, while the scale of the ecological effects of human impacts is often overestimated.

However, expressing a strong desire to protect nature does not, by itself, show greater environmental awareness. These values are often expressed in symbolic actions, but do not necessarily lead to less energy and material consumption or a reduction in environmental harm otherwise [8].

In principle, the use of biomass is a prominent example of the sustainable utilization of natural resources, since the reproduction cycle, i.e., the material and energy flow, can be used for the benefit of humanity. It is sustainable as long as (1) the level of utilization does not exceed biomass growth so that the growing stock is not reduced, (2) the natural values are preserved, and (3) there are no drastic negative social impacts. One of the key arguments supporting biomass utilization is that its net environmental impacts are more favorable than utilizing non-renewable resources, which entails one-way material and energy flow (substitution effect) [9,10]. However, criticisms highlight that this principle does not always prevail, and the utilization may lead to waste of resources. In the case of biomass use for energy, this waste is usually due to the low efficiency of production, from growing and transporting the biomass through energy generation, and using it in a wasteful way [3]. The three most common threats to sustainable fuelwood use in practice are: (1) long-distance transportation [11], (2) low-efficiency combustion using obsolete technology in large heat-generation plants, and (3) inefficient fuel use under conditions of energy poverty. The main arguments around fuelwood use can be grouped into three broad dimensions—economic contribution, environmental impacts, and regulatory effects—across the production and consumption sides of the system (Table 1).

Table 1. The main sustainability arguments related to fuelwood use, grouped by economic contribution, environmental impacts, and regulatory effects across the production and consumption sides of the supply chain [4].

	Production	**Consumption**
Contribution to economy	Added value to the regional economy	Energy security improvement through diversification
Environmental impacts	Forest disturbance	Air pollution
Regulatory effects	Circular carbon flow Competition to other wood products serving as carbon pools	

Although fuelwood use is widely discussed, existing evidence remains fragmented across supply chain stages, technologies, environmental effects, and socioeconomic contexts. Therefore, the aim of this review is to examine the environmental and socioeconomic impacts of fuelwood use across the supply chain, focusing on how fuelwood and related wood energy products are defined, what production and consumption technologies and impacts are reported, and how poverty-related problems and energy transition pathways shape the sustainability of fuelwood use.

2. Literature Search and Screening Methodology

This systematic review is reported in accordance with the PRISMA 2020 guidelines [12]. The review used a systematic search, predefined eligibility criteria, standardized data extraction, and thematic coding, followed by narrative synthesis supported by descriptive publication counts. The review was not registered, and a separate review protocol was not prepared. The search strategy, eligibility criteria, selection process, coding framework and synthesis methods are described below and in the Supplementary Materials.

A systematic literature search was conducted using the Web of Science Core Collection to identify the literature addressing fuelwood, firewood, and wood energy systems, with particular attention to terminology, wood fuel product types, energy production equipment, environmental effects, carbon cycle implications, poverty-related problems, and links to energy transitions.

Web of Science Core Collection was selected as the sole bibliographic database because its multidisciplinary coverage and field-specific search functions suited the environmental, technical, health, and socioeconomic scope of the review. Reliance on a single database may nevertheless have omitted relevant publications indexed elsewhere. Manual searching supplemented the database search, but did not eliminate this limitation.

The search strategy was designed to capture studies covering different stages of the fuelwood system, from forest harvesting and collection to processing, transport, trade, household or large-scale use, combustion, ash handling, and broader socioeconomic and environmental consequences. The literature search was completed on 2 April 2026; no records published or indexed after this date were considered.

The full Web of Science search string combined abstract, title, and topic fields: actor, user, and supply chain-related terms were searched in the abstract field; fuelwood-related terms were searched in the title field; and production, use, and impact-related terms were searched in topic fields. The complete search string and applied filters are provided in Supplementary Material S1.

No geographical restrictions were applied during study selection; relevant publications were eligible regardless of the country or region investigated. Although the search query included geographical terms relating to Europe and the United States, retrieved publications concerning other regions were also assessed and included when they met the eligibility criteria.

Open access status was not an exclusion criterion in the final dataset. Nine publications whose full texts had initially been unavailable were subsequently obtained, assessed and included. Searches were restricted to articles and review papers and conference proceedings published in English. No temporal restrictions were applied.

Studies were eligible if they addressed fuelwood or wood energy systems and contributed to one or more review dimensions, including product types, energy production equipment, environmental effects, efficiency, carbon cycle implications, poverty, or energy transitions. Studies without a clear wood fuel or wood energy component were excluded. For all studies meeting the eligibility criteria, relevant information was systematically extracted using a predefined study screening and data-extraction table.

Study selection followed a two-stage process consisting of (i) title and abstract screening and (ii) full-text eligibility assessment. Both stages were performed by one reviewer. Uncertain eligibility decisions were discussed with the other authors and resolved by consensus. Titles and abstracts were assessed against the predefined eligibility criteria, and records considered potentially relevant were retained for full-text assessment. Full-text articles meeting the eligibility criteria were included in the synthesis, and additional relevant studies identified by manual search were assessed using the same criteria. The study selection process is summarized in the PRISMA flow diagram (Figure 1), and the completed PRISMA 2020 checklist is provided in Supplementary Material S2.

The literature search identified 114 records in Web of Science. After excluding five non-English records, 109 records underwent title and abstract screening. Eleven records were excluded at this stage, and the remaining 98 publications were included following full-text assessment. Three additional publications were identified through manual searching, giving a final review dataset of 101 publications (Figure 1).

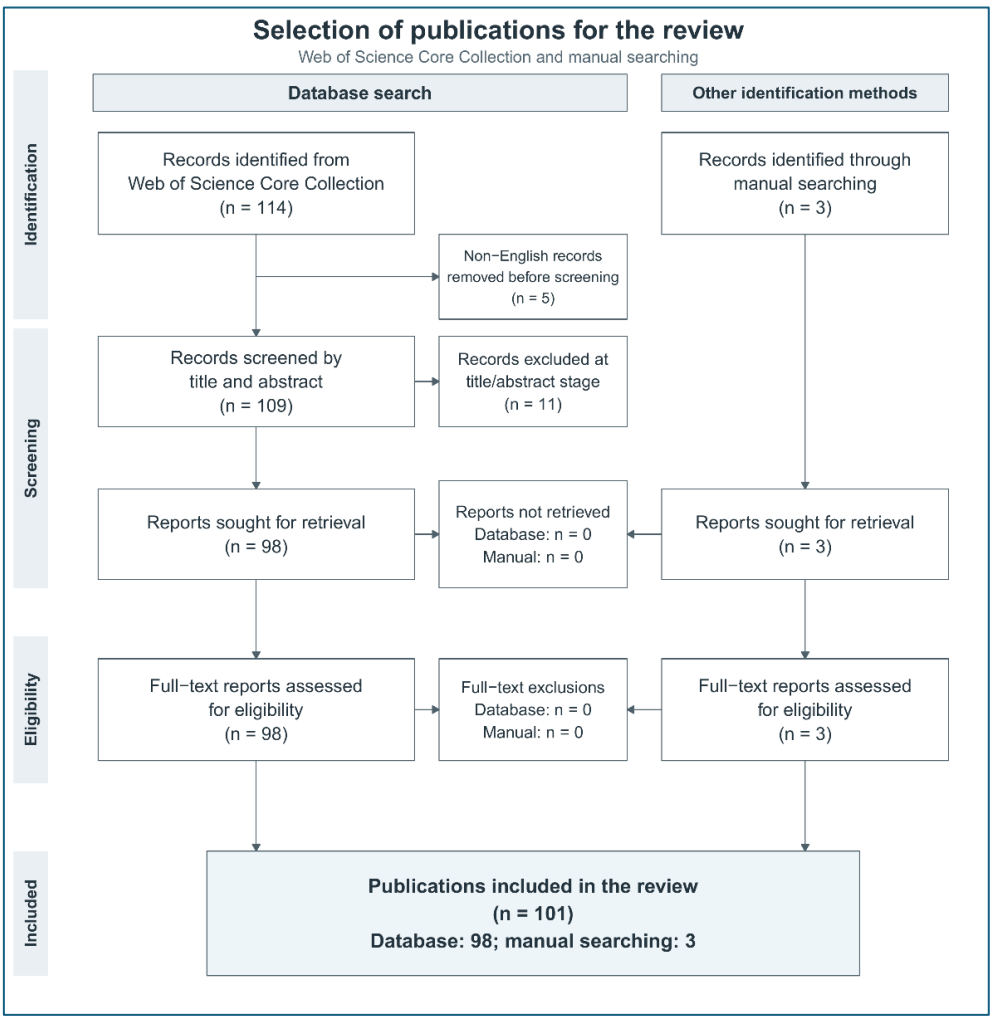


Figure 1. PRISMA flow diagram of the literature selection process.

Extracted variables included country, evidence type, energy transition direction, energy transition aspect, type of wood product, large-scale and household energy production equipment, perceived energy efficiency of combustion, and environmental effects related to tree felling, transportation, combustion, ash handling, household air pollution, poverty-related problems, and carbon cycle implications. Each study was coded using predefined categories listed in Supplementary Material S3. When several effects were reported, all relevant categories were recorded, while unclear or missing information was marked as not available.

Coding categories were not mutually exclusive. Each publication was counted once within each applicable category, but could contribute to several categories. Frequencies therefore describe how often particular themes were reported within the included publications; they do not measure effect magnitude, establish causality or indicate the strength of evidence. Included reviews may also draw on primary studies represented elsewhere in the dataset. We did not formally assess this overlap or adjust the publication counts for it.

Data from each included publication were extracted by one reviewer using the standardized extraction form. The extracted data and categorizations were subsequently reviewed and discussed by the author team. Uncertain or inconsistent classifications were re-examined against the full texts and resolved through discussion. Data extraction was not performed independently in duplicate.

The findings were synthesized narratively and summarized using descriptive publication counts. The evidence combined experiments, surveys, modeling, life-cycle

assessments, and reviews addressing different outcomes, technologies, comparators, system boundaries, and time horizons. Data extraction focused on thematic categories rather than a common set of effect estimates and associated uncertainties. Consequently, no pooled effect estimates were calculated. No formal assessment of methodological quality, risk of bias or certainty of evidence was undertaken. Publication counts were not weighted by study quality. This limits conclusions about the robustness of reported effects and the strength of the resulting recommendations.

3. Results

3.1. General Study Characteristics

The characteristics of the reviewed studies are summarized in Appendix A, Table A1, which reports the coded fuelwood-related dimensions for each study, including country, evidence type, energy transition direction, fuelwood product type, energy production equipment, environmental effects, carbon cycle effects, and poverty-related problems.

The evidence base was dominated by modeling studies and surveys, indicating a strong focus on scenario analysis, resource assessment, market and policy effects, and household-level fuelwood practices (Figure 2). Modeling studies mainly assessed future fuelwood supply, biomass availability, or policy scenarios, supply chain logistics, forest-sector market responses, greenhouse gas effects, carbon storage, and trade-offs between wood energy use and other ecosystem or economic objectives. The survey studies mainly examined fuelwood consumption patterns, household heating practices, demand drivers, and market behavior. LCA studies mainly assessed the environmental performance of wood energy supply chains, identifying hotspots such as harvesting or extraction, chipping, pelletization, transport, and combustion, as well as the effects of substituting fossil fuels with wood energy. Experimental and field-measurement studies mainly focused on combustion emissions, stove performance, emission control technologies, and fuel properties.

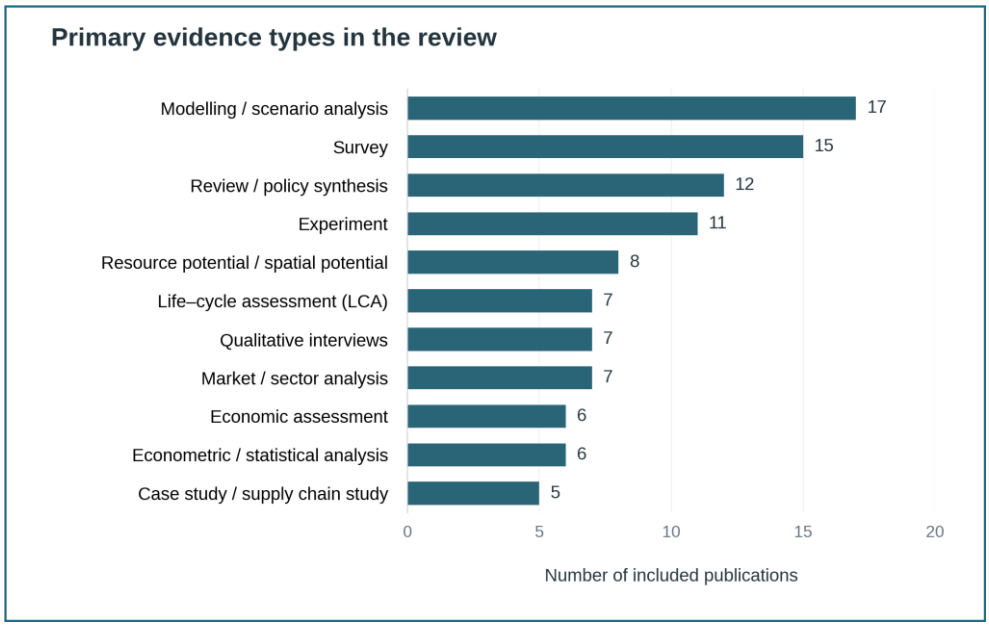


Figure 2. Type of evidence represented in the reviewed studies.

The reviewed studies were geographically diverse, but most were concentrated in Europe. The most frequent individual country was the USA, followed by Italy, while Sweden, Switzerland, Germany, and Turkey also appeared repeatedly. Several studies used broader spatial categories, especially Europe and Global, showing that part of the

literature addressed regional or international patterns rather than single-country case studies (Figure 3).

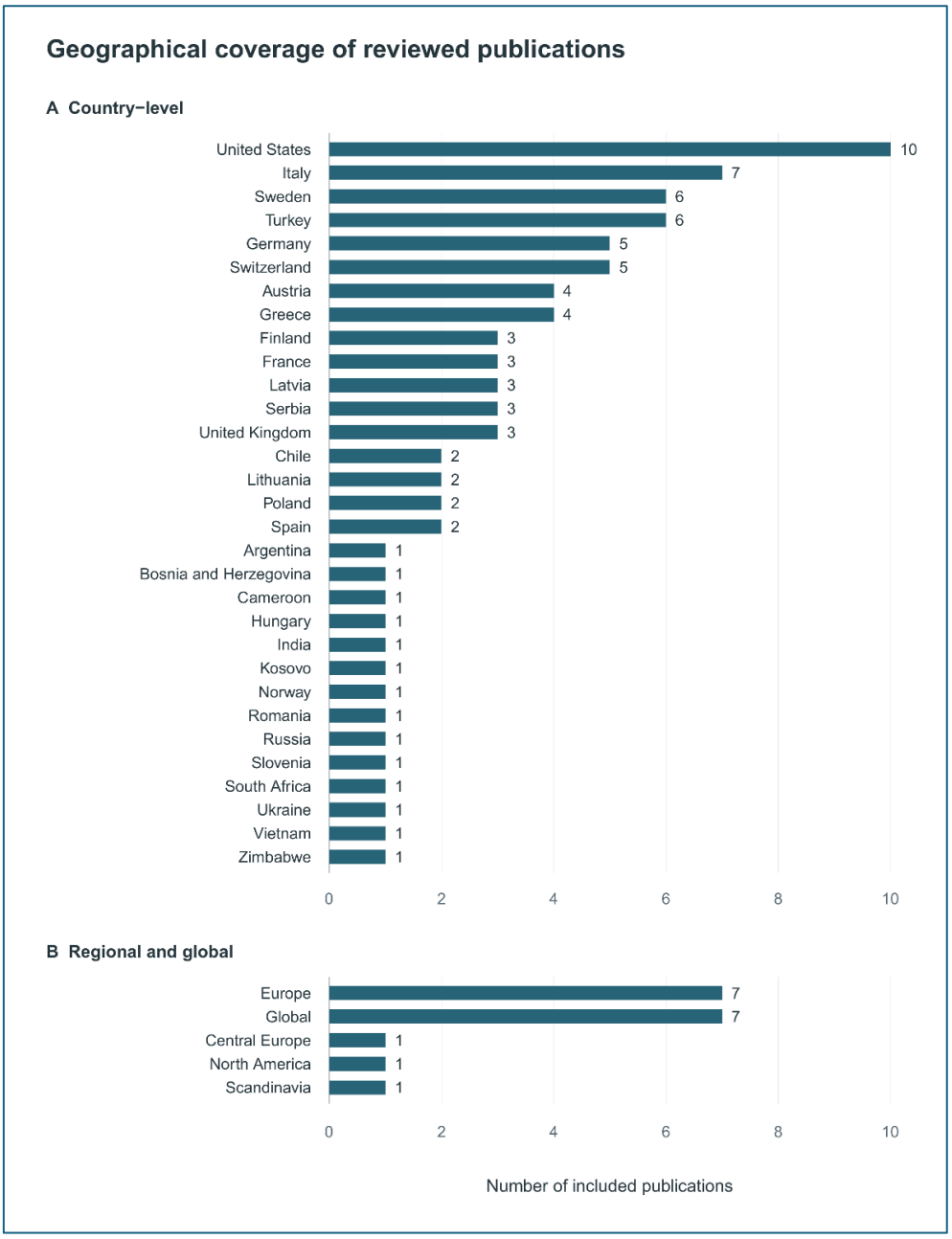


Figure 3. Geographical distribution of the reviewed studies. The bars show the number of studies referring to each country or broader geographical region.

3.2. Terminology and Scope of Wood-Based Fuels in the Reviewed Literature

The reviewed studies used a wide range of terms to describe wood-based fuels and biomass used for energy. The most frequent terms were fuelwood, wood fuel, firewood, wood energy, energy wood, woody biomass, dendromass, wood energy biomass, forest bioenergy, and solid biomass. Several studies also used more specific or context-dependent expressions such as wood chips, wood pellets, forest fuel chips, forest residues, etc.

The majority of the reviewed studies did not provide a formal definition of wood fuel, fuelwood, or firewood, and the terminology was often applied according to the specific product category, forest assortment, or energy-use context of each study. Where definitions were given, they varied considerably in scope.

Mazure & Grinberga-Zalite [13], referring to the Joint Forest Sector Questionnaire, define fuelwood as roundwood used as fuel for cooking, heating, or power production. In this definition, fuelwood includes wood harvested from main stems, branches, and other parts of trees, as well as wood used for charcoal production and wood chips made directly from roundwood for fuel, while excluding wood charcoal itself.

Hillring [14], citing the now outdated CEN/TS 14588:2003 [15] terminology, used a broader definition of wood fuel as all types of biofuels originating directly or indirectly from woody biomass, with woody biomass referring to biomass from trees, bushes, and shrubs. Although ISO 16559:2022 [16] was not cited in the reviewed studies, its updated vocabulary provides a useful distinction between related terms: wood fuel is defined as solid wood-based fuel; fuelwood as wood fuel in which the original composition of the wood is maintained and which has only been treated mechanically; and firewood as cut and split, oven-ready energy wood, usually used in household wood-burning appliances such as stoves, fireplaces, and central heating systems.

Other studies used narrower, study-specific meanings. Bouget et al. [17], based on the forest bioenergy categories of Röser et al. [18], distinguish five sources of forest bioenergy. However, they used the term fuelwood only for wood energy crops, wood from precommercial thinning, and forest residues from commercial harvesting, excluding waste wood and pulp-mill residues such as black liquor from their working definition. Erni et al. [19], in contrast, define wood fuel broadly as woody biomass used for energy production, including forest wood, trees outside forests, wood residues, and waste wood. Perednis et al. [20] identify three main fuelwood resources: firewood from main and cultivation cuttings, residues from the wood-processing industry, and forest cutting residues, while defining firewood more narrowly as the part of the stem that cannot be processed into higher-value products. Mydlarz & Wieruszewski [21] do not provide a formal definition, but operationalize firewood through Polish forest assortment classes, including small-sized firewood, wood used as fuel, and energy wood.

Overall, the reviewed literature shows no consistent use of the terms wood fuel, fuelwood, and firewood. The concepts range from broad definitions covering all woody biomass used for energy, including residues and waste wood, to narrow definitions focused on mechanically processed stemwood or household-ready firewood. This variation is important because the environmental implications of fuelwood use differ depending on whether studies refer to stemwood, harvesting residues, thinning material, short-rotation energy crops, industrial by-products, or post-consumer waste wood.

In this review, "wood-based fuels" encompasses fuels derived from woody biomass, including firewood, chips, pellets, briquettes, charcoal, industrial residues, recovered wood, and wood-derived liquid or gaseous fuels. "Fuelwood" is used interchangeably with this broad term unless a source-specific definition or original coding category is being discussed. "Firewood" refers specifically to logs, split wood and cut branches used directly for combustion.

3.3. Types of Wood Products for Energy Purposes

The reviewed publications reported a wide range of wood products used for energy purposes (Figure 4). The most frequently mentioned categories were fuelwood, wood chips, pellets, logging residues, wood-processing residues, logwood, briquettes, wood residues, and roundwood. Other categories included materials such as bark, stumps and sawdust, recovered wood, charcoal, and wood-derived energy carriers such as pulping liquor and gaseous biofuels.

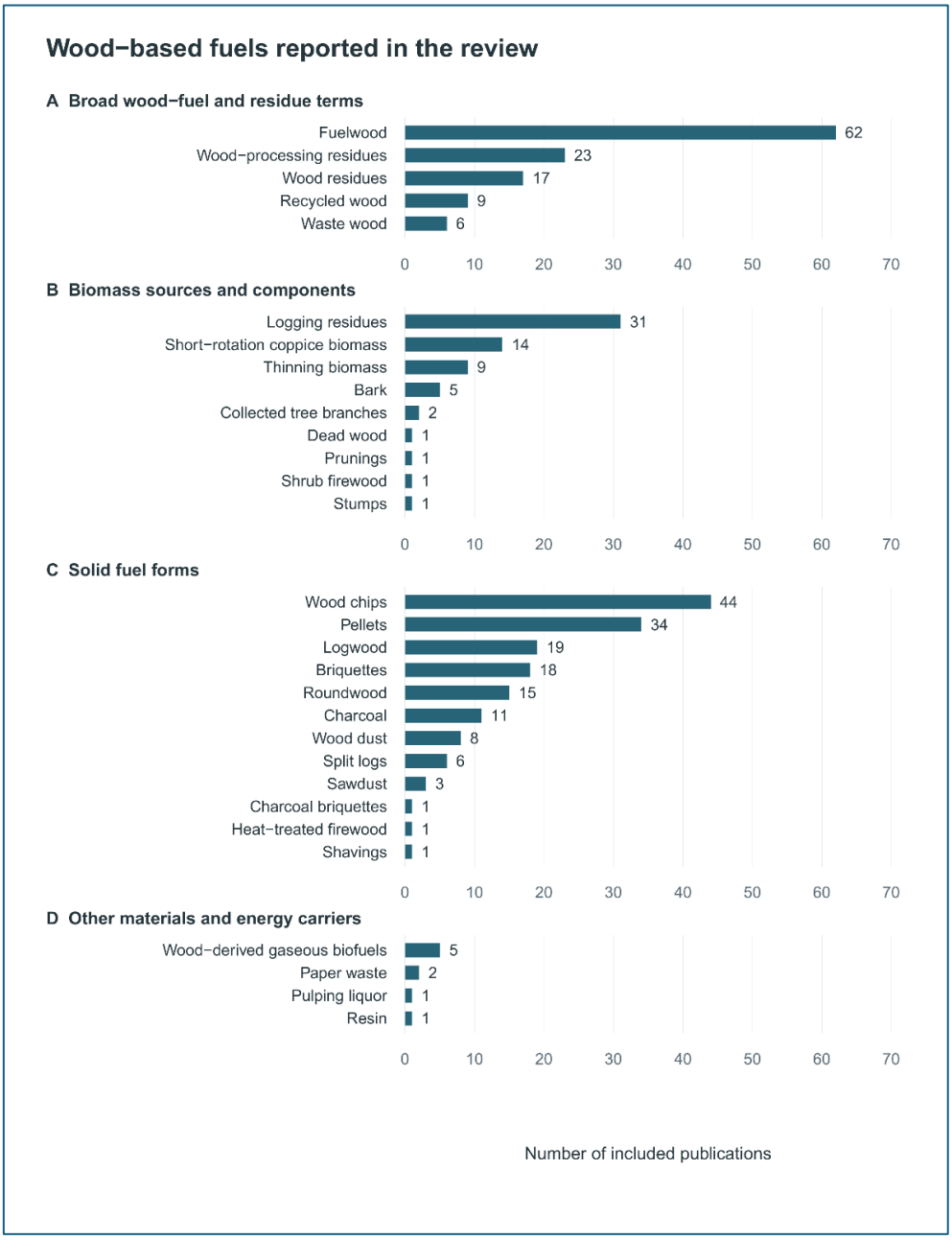
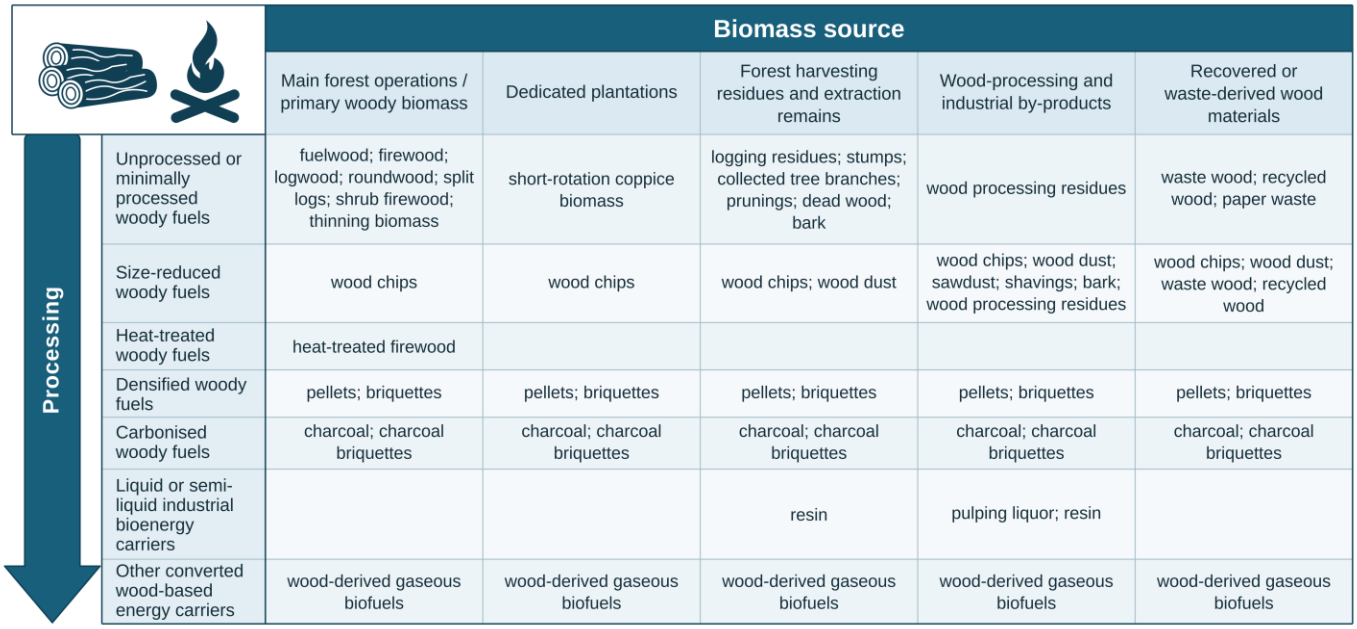


Figure 4. Wood product categories reported in the reviewed publications. Categories are not mutually exclusive.

The reported terminology encompasses several overlapping classification dimensions, including biomass origin, material type, and product form. Logging residues and wood-processing residues refer to biomass origin, whereas chips, pellets, briquettes, and charcoal denote processed product forms. A given product form may originate from multiple biomass sources; for example, wood chips may be produced from roundwood, harvesting residues, or processing by-products. Individual publications may therefore contribute to more than one category. Figure 5 presents an analytical classification of the reported products according to biomass source and processing type. Distinguishing these dimensions is relevant to the synthesis of environmental impacts. Biomass source provides context for assessing harvesting, residue removal, and the allocation of wood between material and energy uses, while product form informs the interpretation of processing, transport, and combustion impacts. Identical product designations may therefore encompass different supply chains with distinct environmental implications. Both

biomass source and product form should consequently be considered when interpreting the effects reported in subsequent sections.

Technical properties, including calorific value and moisture content, were not consistently reported across the reviewed publications and remained outside the standardized data-extraction framework of this review. The classification therefore provides a descriptive overview of the products represented in the evidence base without assigning standardized technical specifications or ranking their environmental performance.



Processing	Biomass source				
	Main forest operations / primary woody biomass	Dedicated plantations	Forest harvesting residues and extraction remains	Wood-processing and industrial by-products	Recovered or waste-derived wood materials
Unprocessed or minimally processed woody fuels	fuelwood; firewood; logwood; roundwood; split logs; shrub firewood; thinning biomass	short-rotation coppice biomass	logging residues; stumps; collected tree branches; prunings; dead wood; bark	wood processing residues	waste wood; recycled wood; paper waste
Size-reduced woody fuels	wood chips	wood chips	wood chips; wood dust	wood chips; wood dust; sawdust; shavings; bark; wood processing residues	wood chips; wood dust; waste wood; recycled wood
Heat-treated woody fuels	heat-treated firewood				
Densified woody fuels	pellets; briquettes	pellets; briquettes	pellets; briquettes	pellets; briquettes	pellets; briquettes
Carbonised woody fuels	charcoal; charcoal briquettes	charcoal; charcoal briquettes	charcoal; charcoal briquettes	charcoal; charcoal briquettes	charcoal; charcoal briquettes
Liquid or semi-liquid industrial bioenergy carriers			resin	pulping liquor; resin	
Other converted wood-based energy carriers	wood-derived gaseous biofuels	wood-derived gaseous biofuels	wood-derived gaseous biofuels	wood-derived gaseous biofuels	wood-derived gaseous biofuels

Figure 5. Analytical grouping of reported wood products by biomass source and processing type. Groups are not mutually exclusive; products may appear in multiple cells where several source–processing combinations are possible.

3.4. Large-Scale Energy Production Equipment

The reviewed studies reported several large-scale technologies using wood-based fuels for heat and/or electricity production (Figure 6). District or collective heating was the most frequently mentioned category [22,23], followed by power-only electricity generation [24,25], combined heat and power systems (CHP) [26,27], large boiler or furnace systems [28], and industrial heat or steam production [29]. Co-firing or hybrid fossil–biomass systems were also reported, reflecting the role of wood energy in transitional energy systems. Thermochemical conversion appeared less frequently and represents a distinct conversion pathway rather than a single equipment type. It may include gasifiers, pyrolysis reactors, torrefaction units, and related gas-cleaning or upgrading equipment. For example, Rusanova et al. [27] describe a route in which solid biofuels are gasified, the resulting gas is cleaned, prepared for methane production, dried, and compressed before being injected into the natural gas grid or used on site.

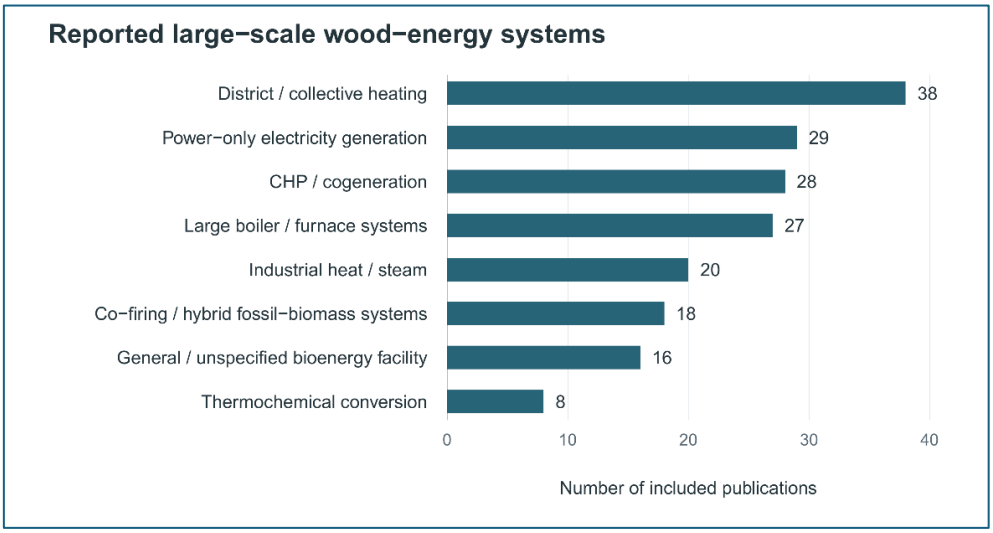


Figure 6. Large-scale wood energy production technologies reported in the reviewed studies.

3.5. Household Energy Production Equipment

The reviewed studies discussed a broad range of household and small-scale energy production equipment (Figure 7). The most frequently mentioned category was general household heating systems, which appeared in 47 studies. This indicates that many papers addressed household wood energy use at a relatively broad level, without specifying the exact appliance type. Among the more specific appliance categories, stoves and room heaters were the most common, appearing in 34 studies [28,30–32]. This reflects the central role of individual room-heating appliances in household fuelwood use, especially where wood is used directly for space heating. Cookstoves were also frequent, appearing in 19 studies, showing that household wood use is not limited to heating, but is also strongly connected to cooking practices in some geographical and socioeconomic contexts [33–37]. Fireplaces and open fires were mentioned in 16 studies, usually representing more traditional or less efficient forms of direct combustion [2,31,38]. Boiler-based systems were also present in the literature; central heating appeared in 15 studies, suggesting that wood fuel is also discussed in relation to whole-house heating systems [39–41]. Pellet appliances appeared in 14 studies [42–44]. Less frequently mentioned categories included emission control and combustion control devices [32,45,46] and small farm heating systems [47].

Overall, the results show that household wood energy use is mainly discussed through general domestic heating systems and direct-combustion appliances; more modern or specialized systems, such as pellet appliances, combustion control technologies, wood chip heating, and micro-CHP [48], appeared less frequently. This pattern suggests that the reviewed literature primarily focuses on conventional household wood use, while the technological modernisation of household-scale wood energy systems is present but less dominant.

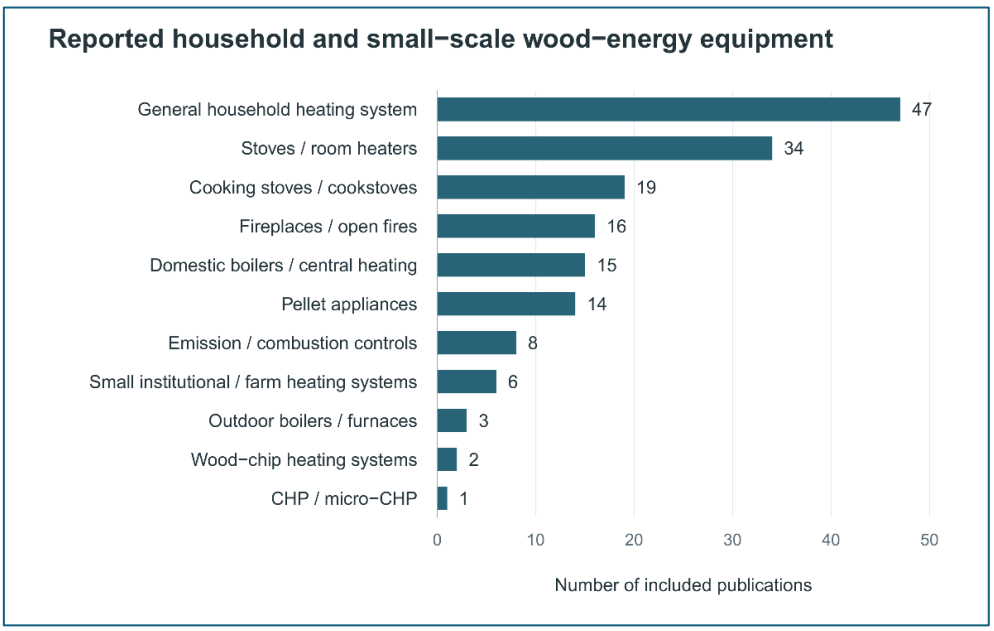


Figure 7. Household wood energy production equipment reported in the reviewed studies.

3.6. Environmental Effects

3.6.1. Effects of Tree Felling

The reviewed studies show that tree felling is associated with a wide range of environmental effects, ranging from direct changes in growing stock and stand development to broader consequences for soil, nutrient cycling, biodiversity, and ecosystem services (Figure 8). Overall, the effects are strongly context dependent. Intensive, poorly regulated or repeated felling is generally linked to negative outcomes such as reduced growing stock, forest degradation, biodiversity decline, and reduced ecosystem service provision [17,24,34,38,49,50]. However, several studies also reported positive effects, suggesting that planned or selective felling can support regeneration, improve growth conditions, increase structural diversity, or contribute to long-term forest management objectives [10,45,51–53].

The most concrete and frequently reported effects were related to growing stock and stand growth. Reduced standing stocks were reported in 17 studies, reflecting the direct removal of tree biomass through felling [19,40,54–56]. Reduced growth appeared in ten studies, suggesting that tree felling can negatively affect stand productivity when it is associated with overharvesting, forest degradation, soil disturbance, poor regeneration, or repeated biomass removal [25,57,58].

These effects also have carbon cycle implications, including changes in carbon stock and carbon sink capacity; however, these aspects are discussed in detail in subchapter 3.6.6 on the carbon cycle. At the same time, some studies reported increased standing stocks or increased growth. This indicates that tree felling is not always interpreted as environmentally harmful. In managed forests, selective harvesting, thinning, or regeneration-oriented felling may reduce competition, improve growing conditions for remaining trees, and support stand renewal, depending on harvesting intensity, timing, and silvicultural context [1,10,51,59,60].

A second important group of effects relates to soil disturbance [20,22,56,57]. Tree felling is often accompanied by machinery traffic, extraction operations and the creation of skid trails or access routes. These activities may cause soil compaction, rutting, erosion, and exposure of bare soil, especially on wet, steep, or otherwise sensitive sites. Soil disturbance can also reduce water infiltration, damage roots and impair natural regeneration

[57]. Although soil effects may be less visible than the immediate removal of trees, they can have long-term consequences for site productivity and forest recovery.

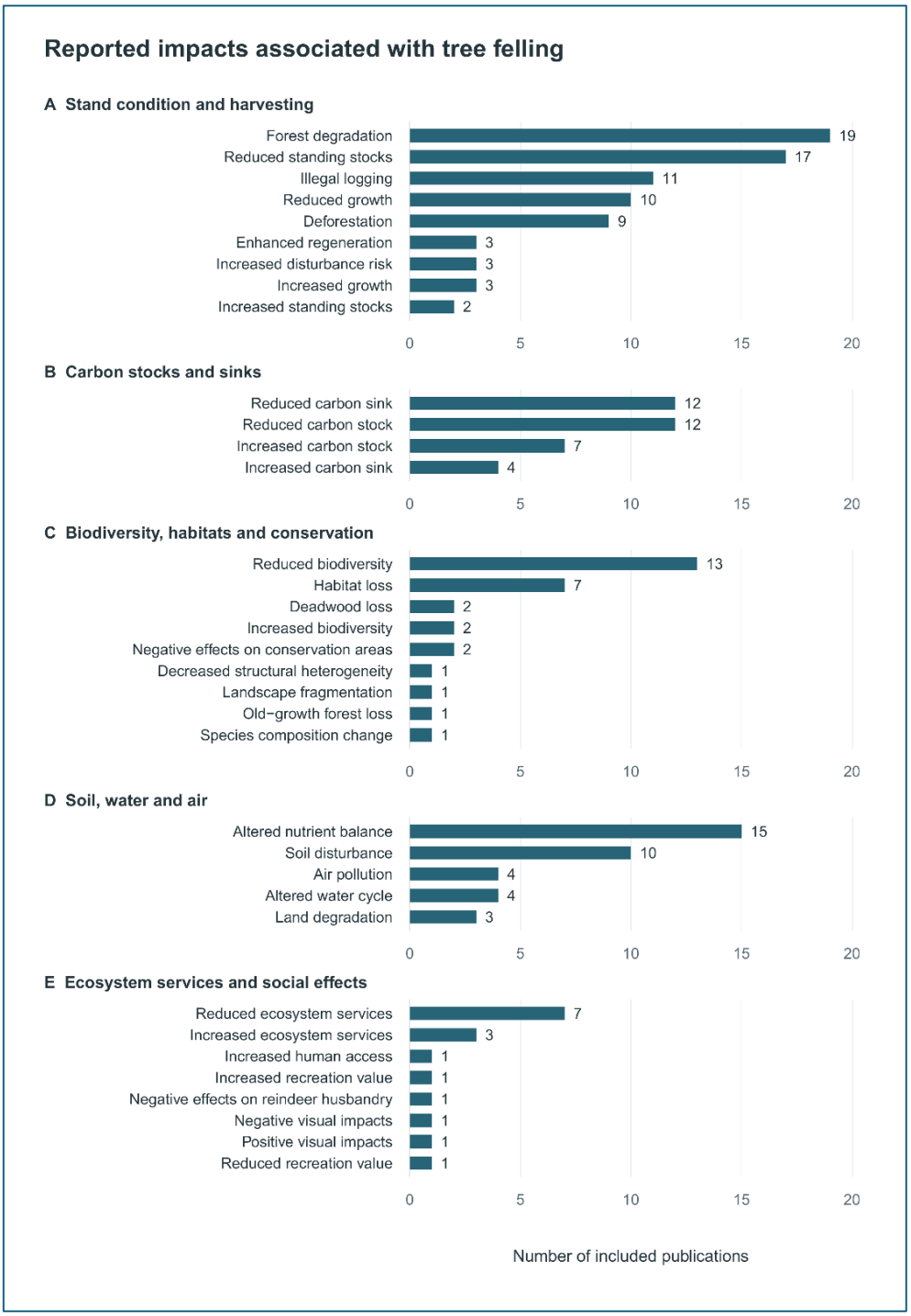


Figure 8. Environmental effects of tree felling reported in the reviewed studies.

Closely connected to soil impacts are changes in nutrient cycling. Altered nutrient balance was one of the strongly represented effects in the reviewed evidence. Felling removes biomass from the forest system, and with it, nutrients stored in stems, branches, bark, foliage, and roots. The risk of nutrient depletion is particularly high when whole-tree harvesting, logging-residue removal, or stump extraction is practiced because these operations remove more nutrient-rich biomass than stem-only harvesting [19,22,57,61]. Canopy opening may also alter litter input, decomposition rates, soil temperature, and

soil moisture, further affecting nutrient turnover [57]. Therefore, nutrient-cycle effects not only depend on the amount of wood removed, but also on which biomass fractions are harvested and whether residues are retained on site.

Several studies linked fuelwood-related tree felling to broader forest degradation, particularly in poorer regions where households depend heavily on wood biomass for energy. Arabatzis et al. [24] reported that high biomass-energy dependence in Tanzania contributes to environmental degradation, mainly through deforestation, while long-term, unregulated fuelwood harvesting in Greek mountain forests has also contributed to forest degradation, with social, environmental, and economic consequences. Zafeiriou et al. [38] similarly noted that excessive fuelwood consumption can cause land degradation and forest depletion, especially in developing countries, and described the historical degradation of Greek oak forests due to intensive cutting and overgrazing. Atyi et al. [34] emphasized that fuelwood remains central to household energy supply in Africa, making forest degradation a key concern in poverty-related energy contexts. Vasquez Lavin et al. [62] also linked high biomass consumption and expanding urban wood markets to deforestation and degradation of communal and native forests. Illegal logging was also notable in the evidence, showing that the environmental effects of felling are closely linked to governance, management quality, and enforcement [14,63,64].

Biodiversity effects were also widely represented in the reviewed evidence. Bouget et al. [17] emphasize that fuelwood-driven changes in forestry can affect forest biodiversity at both stand and landscape scales. They mainly frame biodiversity impacts through the removal of deadwood, logging residues, and stumps, which reduces habitat availability for saproxylic organisms and modifies forest-floor and soil-related habitats for other species. In addition, they state that increased internal forest edges may threaten species associated with interior forest conditions. Cardoso et al. [50] add a complementary perspective by showing that repeated fuelwood collection from native shrubs can create sustained pressure on local vegetation and may contribute to future biodiversity decline. This indicates that biodiversity impacts may also arise from recurrent local harvesting of native woody vegetation, particularly in ecosystems where shrubs contribute substantially to habitat structure and species composition. Eggers et al. [65] further show that the magnitude of these impacts depends strongly on management strategy and landscape-level planning. Their results indicate that intensified wood fuel extraction may create trade-offs with habitat-related biodiversity indicators, including old forest, mature broadleaf-rich stands, large trees, and deadwood, but that careful planning and retention of key habitat structures can reduce these trade-offs. Some studies also reported increased biodiversity or enhanced regeneration, suggesting that biodiversity outcomes depend strongly on harvesting intensity, retained habitat structures, landscape context, post-felling management, and the application of sustainable forest management practices [66].

The broader consequences of tree felling are reflected in changes in ecosystem services. Reduced ecosystem services appeared more often than increased ecosystem services, indicating that many studies associate tree felling with declines in habitat provision, soil protection, water regulation, recreation, conservation value, and landscape quality [65,67–70]. Reduced recreation value, negative visual impacts, and negative effects on conservation areas show that tree felling is also evaluated through social and cultural dimensions, not only through biophysical indicators [65,69]. Nevertheless, increased ecosystem services and increased recreation value were also reported in some studies [26,59]. These positive outcomes may occur where felling improves stand accessibility, reduces safety risks, supports regeneration, restores desired species composition, or contributes to long-term forest resilience [2,47]. Negative effects on reindeer husbandry appeared in one study [65], which reported that tree felling can reduce or fragment grazing areas, disturb migration routes, increase human access, and alter forest structures that support winter

forage, such as ground and arboreal lichens. This highlights that some effects of tree felling may be rare in the literature, but highly relevant in specific regional and cultural contexts.

3.6.2. Effects of Transportation

Transportation-related impacts were dominated by effects associated with distance, logistics, and fossil fuel use (Figure 9). The most frequently reported category was long-distance transport burden, followed by logistics and storage burden and reduced economic and environmental feasibility of extraction. This pattern indicates that transportation is a central determinant of the environmental performance of fuelwood supply chains, particularly where biomass is moved over large distances or where collection, storage, and delivery are poorly optimized.

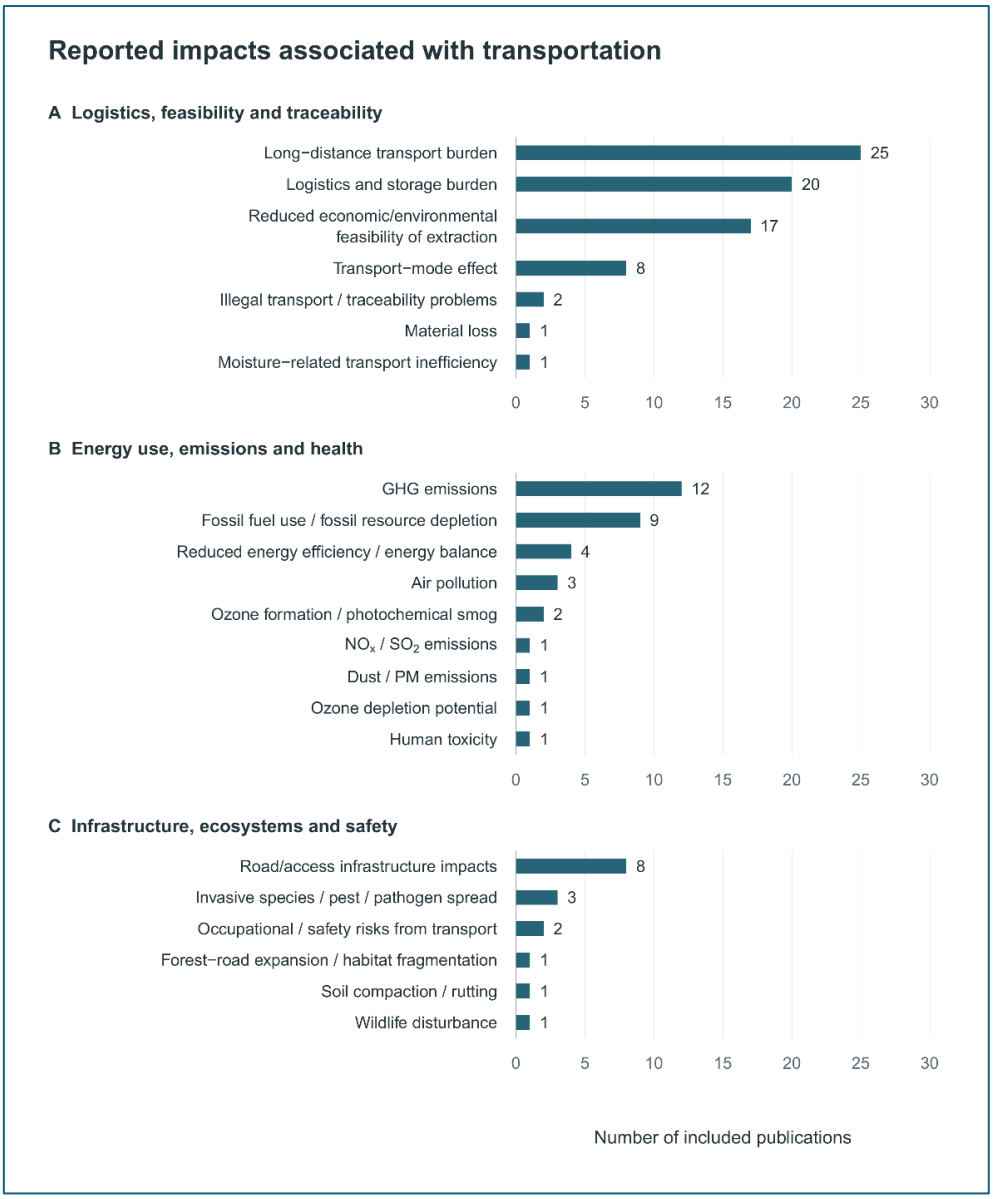


Figure 9. Environmental effects of transportation identified in the reviewed studies.

Although fuelwood use is often discussed in relation to the biogenic carbon cycle, transportation represents an additional fossil energy input. This is reflected in the frequent occurrence of greenhouse gas (GHG) emissions and fossil fuel use or fossil resource depletion in the reviewed studies [30,40,48,71]. Transport emissions mainly arise from fuel use during loading, handling, and delivery, and therefore occur outside the closed forest

carbon cycle. Consequently, long-distance or inefficient transport can reduce the climate benefits expected from fuelwood use, especially when low-value, bulky, or high-moisture material is transported [72,73].

Transport also contributes to air pollution, although this appeared less frequently than GHG emissions or distance-related burdens. Reported air pollution effects included particulate matter, NO_x/SO_x emissions and ozone formation associated with photochemical smog. These impacts are particularly relevant where road transport dominates, vehicles are inefficient, or repeated small-load deliveries are common.

The category "transport-mode effect" refers to the influence of the chosen transport system—such as road, rail or combined transport—on fuel use, emissions, costs and overall environmental burden. This category further emphasizes that the environmental consequences of transportation depend not only on distance, but also on how biomass is moved. For longer distances, rail transport may offer lower fuel use and emissions per unit of delivered biomass than road transport, particularly when large volumes are transported [73,74]. In contrast, poorly loaded vehicles or repeated small-scale road deliveries can increase fuel consumption, emissions, and costs [34]. Therefore, distance, vehicle type, load efficiency and transport organization should be evaluated together when assessing the environmental performance of fuelwood systems [75].

Further transportation-related impacts concern infrastructure. Road infrastructure impacts appeared more frequently than more specific categories such as forest road expansion, habitat fragmentation, soil compaction, wildlife disturbance, and occupational and safety risks from transport, suggesting that the reviewed studies often addressed infrastructure effects in broader terms [17,61,76].

Although reported less frequently in the reviewed evidence, invasive species, pest, and pathogen spread represent a major transportation-related concern because introduced pests and pathogens can cause severe and long-lasting damage to forest ecosystems. Solano et al. [77] showed that firewood movement is an important human-mediated pathway for forest pest dispersal in North America. This pathway is relevant because wood-inhabiting organisms can survive in logs and firewood and may be transported by recreational users or households far beyond their natural dispersal capacity, particularly when untreated, infested, or non-local firewood is moved between regions or to campsites. The authors emphasize that local firewood use, effective heat treatment or other sanitation measures, consistent monitoring and regulation, improved rule compliance, and public education are needed to reduce pest dispersal through firewood transport.

3.6.3. Health Effects of Combustion

The reviewed literature provides strong evidence that fuelwood burning and combustion are associated with a wide range of environmental and health effects. The most frequently reported effect was GHG emissions, followed by particulate matter (PM) emissions and fossil fuel substitution benefit (Figure 10). This pattern reflects a central tension in the fuelwood literature: fuelwood burning may contribute to fossil fuel substitution, but it also directly releases GHGs and air pollutants [1,10]. The relatively frequent occurrence of carbon neutrality, carbon debt and fossil fuel substitution benefit indicates that the climate implications of fuelwood combustion are often assessed in relation to carbon accounting assumptions and the fossil fuel system being replaced. The broader carbon cycle consequences of fuelwood use are discussed in more detail in Section 3.6.6.

Air pollution-related effects were also frequently reported across the reviewed literature [2,19,66,78]. Health-related effects included respiratory effects, cardiovascular health risk, human toxicity, carcinogenic effects, and broader public health impacts.

The evidence shows that many combustion-related impacts are strongly influenced by combustion quality and appliance performance [2]. The frequent occurrence of categories such as low combustion efficiency and incomplete combustion, poor appliance quality and outdated appliance emissions, stove maloperation emissions, start-up and burn-out high-emission phases, moisture-related emissions, and fuel-quality-related emissions indicates that combustion emissions are shaped by the combined effects of fuel properties, fuel moisture content, appliance design and age, air supply, combustion temperature, emission control technologies, and user behavior.

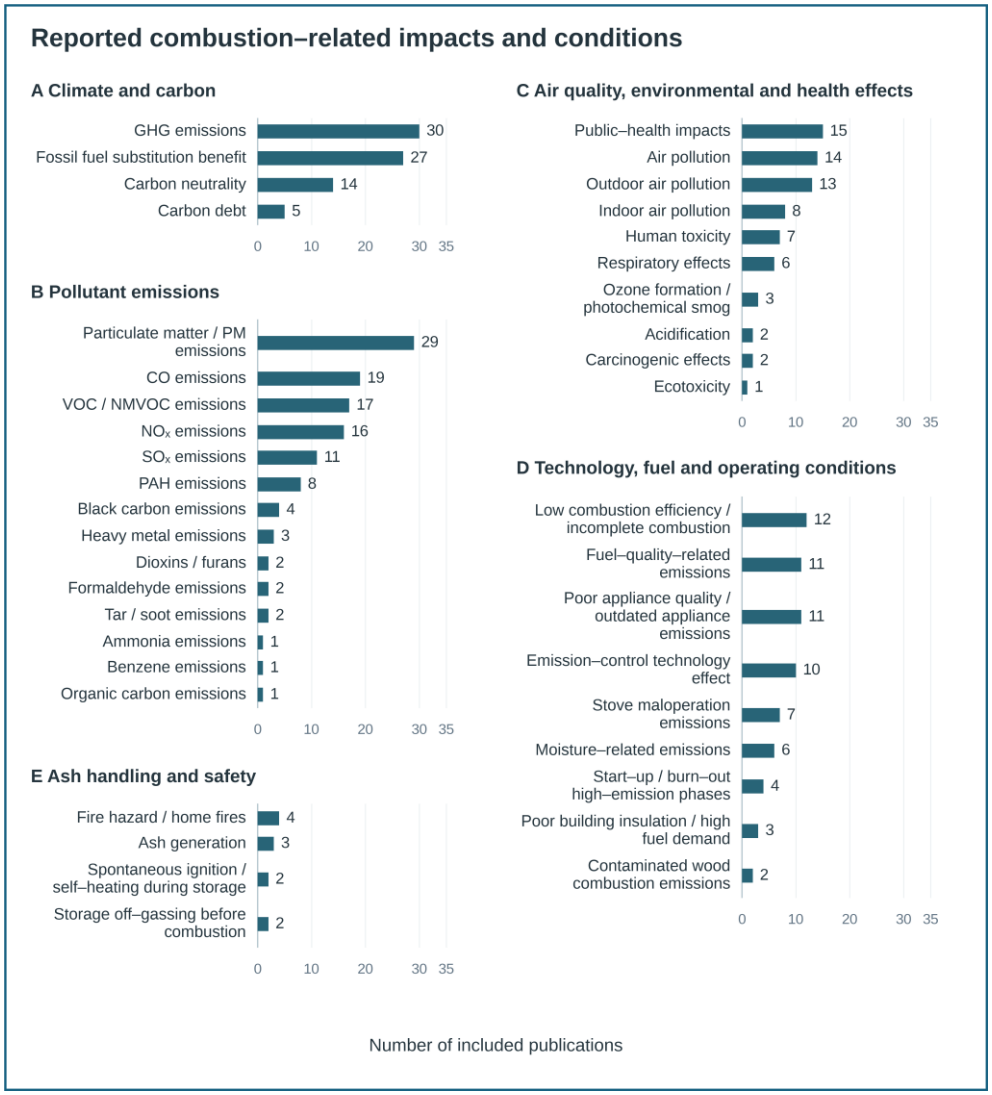


Figure 10. Environmental effects of combustion reported in the reviewed studies.

The distinction between complete and incomplete combustion is important for interpreting these effects (Figure 11). Under complete and well-controlled combustion, emissions are dominated by CO_2, NO_x, SO_x, and ash-derived inorganic particles. These emissions contribute to climate warming, tropospheric ozone formation, acidification, eutrophication, respiratory and cardiovascular health risks, human toxicity, and ecotoxicity [2,78]. Incomplete combustion produces an additional set of pollutants, especially CO, CH_4, Non-Methane Volatile Organic Compounds (NMVOCs), black carbon, organic PM, PAHs, aldehydes, benzene, dioxins, furans, tar, and soot. These pollutants are mainly associated with poor fuel–air mixing, wet fuel, smoldering phases, outdated appliances, poor operation and limited emission control technology [2,31]. Incomplete combustion therefore adds further environmental and health effects, including secondary organic

aerosol formation, acute toxic exposure risk, eye and respiratory tract irritation, and carcinogenic effects, while also intensifying general air pollution and health impacts [2].

Appliance scale is particularly important. Tomlin [2] highlights domestic wood burning as especially problematic for PM2.5 because small appliances often operate under incomplete combustion and have limited emission control options. Residential biomass appliances are therefore an important contributor to fine particulate emissions in Europe [2,39,71]. In contrast, larger combustion plants can generally apply better combustion control and flue-gas cleaning technologies, while small domestic stoves and fireplaces are more difficult to control. However, emissions from household appliances are not determined by appliance type alone: fuel moisture content, user-regulated air supply, start-up and burn-out conditions, and operational practice can strongly influence real-world emissions [2,46,79]. At the same time, modern household appliances, especially well-designed pellet stoves and advanced boilers operated with dry, high-quality fuel, can achieve substantially lower emissions than traditional stoves, open fireplaces, or poorly operated older devices [2,39,63]. By requiring less manual control, these modern systems also minimize the risk of suboptimal user operation [2].

The impact of air pollution from wood burning is strongly influenced by the distance between the pollution source and residential areas. From this perspective, centralized solutions such as district heating systems are generally the most favorable, as they typically operate with higher efficiency and they are likely equipped with appropriate emission control technologies [80]. In contrast, household heating appliances are more problematic because they release pollutants directly into residential areas [81]. Although modern and cleaner technologies are available, outdated appliances are still widely used, and air pollution control devices are uncommon. A particularly severe case occurs when the heating appliance is located inside the dwelling. Pollutants can enter the living space directly when the stove door is opened during use [82], when the appliance or flue system is inadequately sealed, or when an open fire is used. Indoor air pollution can maintain high concentrations of harmful substances in the air for extended periods [83,84].

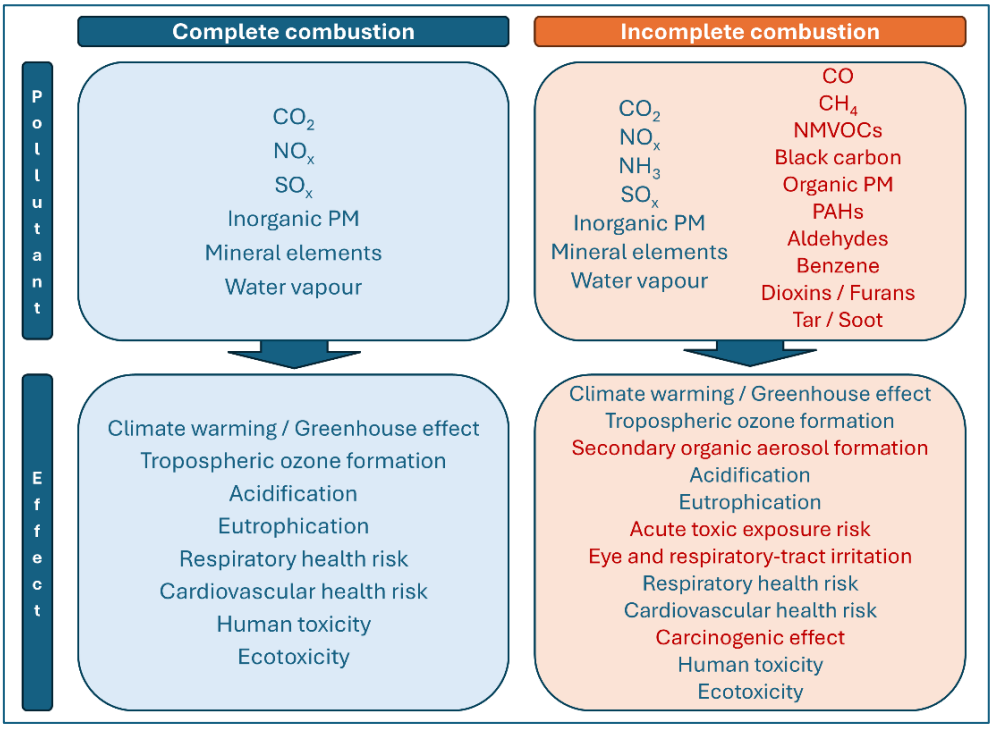


Figure 11. Pollutants and main environmental and health effects associated with complete and incomplete biomass combustion. Blue text indicates emissions and effects that may occur even under

modern, well-controlled combustion, mainly due to biomass carbon, fuel nitrogen/sulphur, and mineral ash content. Red text indicates additional pollutants and effects primarily associated with incomplete combustion, poor fuel–air mixing, wet fuel, outdated appliances, smoldering phases, or poor operation.

3.6.4. Energy Efficiency/Conversion Efficiency

Energy efficiency is the ratio between useful energy output and total energy input. In the context of wood fuel burning, it refers to how effectively the energy stored in wood is converted into useful heat. Wood fuel burning cannot be classified as inherently energy efficient or inefficient; its performance depends on the interaction between appliance design, fuel quality, and operation. Efficient wood fuel combustion can reduce fuel demand and emissions per unit of useful heat, whereas inefficient combustion may increase both biomass consumption and air pollutant emissions.

Most reviewed publications provided mixed assessments or no clear overall judgment of combustion efficiency and were therefore grouped as mixed/no clear judgment (Figure 12). This indicates that efficiency was often mentioned only indirectly, for example, through references to combustion quality, fuel moisture, appliance type, or heat-use conditions, rather than being evaluated as a central outcome [62,63].

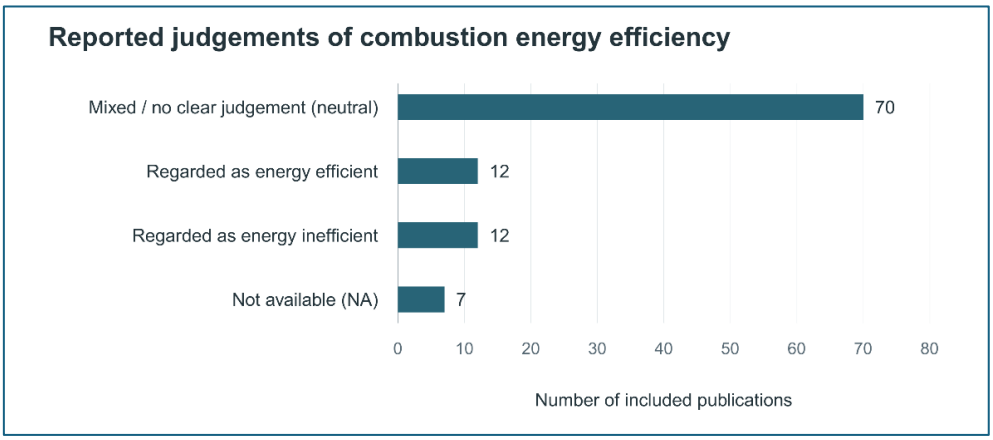


Figure 12. Classification of the reviewed studies according to whether the assessed wood fuel combustion was regarded as energy efficient.

Only a smaller number of studies clearly identified combustion as energy efficient or inefficient. Positive assessments were generally associated with improved or modern appliances, better combustion control, pellet-based systems, dry and homogeneous fuel, or larger-scale systems where combustion conditions and flue-gas treatment can be more effectively controlled [26,27,39,85,86].

Negative assessments were mostly linked to traditional, old, or poorly operated household appliances, incomplete combustion, wet fuel, insufficient air supply, and low heat-use efficiency [23,25,33,70,79,87]. In addition, building-related factors, such as poor insulation, inefficient heat distribution, and high heat losses, can further reduce the useful energy obtained from wood fuel combustion [29,87].

Petrovic [86] highlights that energy efficiency is a central criterion in the assessment and eco-certification of wood fuel burning appliances. The European standards cited in the paper include EN 303-5:2012 [88] for solid-fuel boilers, EN 14785:2006 [89] for wood-pellet stoves, and EN 13240:2001 [90] for room heaters fired by solid fuel. Under EN 303-5:2012 [88], boiler efficiency requirements are defined by efficiency classes and depend on nominal heat output, with Class 5 representing the highest efficiency level. For wood-pellet stoves, EN 14785:2006 [89] requires a minimum efficiency of 75% at nominal heat

output and 70% at partial heat output. Eco-label schemes apply stricter requirements: for example, the Nordic Swan eco-label requires at least 76% efficiency for manually stoked wood fuel stoves and 87% for pellet stoves, while the German Blue Angel and Austrian UZ 37 schemes generally require around 90% efficiency for pellet or automatically stoked wood fuel appliances. These examples show that eco-certified appliances are expected to achieve higher conversion efficiency than appliances meeting only the minimum European standard requirements.

Overall, these findings indicate that modern, eco-certified wood fuel appliances can achieve high energy efficiency and may provide a cleaner and more advanced heating alternative, particularly when combined with dry fuel, appropriate operation, and well-insulated buildings.

3.6.5. Effects of Ash Handling

The reviewed studies addressed ash handling only to a limited extent. The most frequently reported issue was ash generation, although, in many cases, ash was treated as a fuel-quality parameter, operating cost, or household labor burden rather than as a separate environmental impact (Figure 13). Several studies noted that wood fuels, especially pellets or wood chips, can produce less ash than other solid fuels such as coal or dung, which may reduce handling, cleaning, disposal, and maintenance burdens [50,91]. However, ash-disposal impacts were usually not assessed separately, even where ash management was included within broader life-cycle boundaries [30].

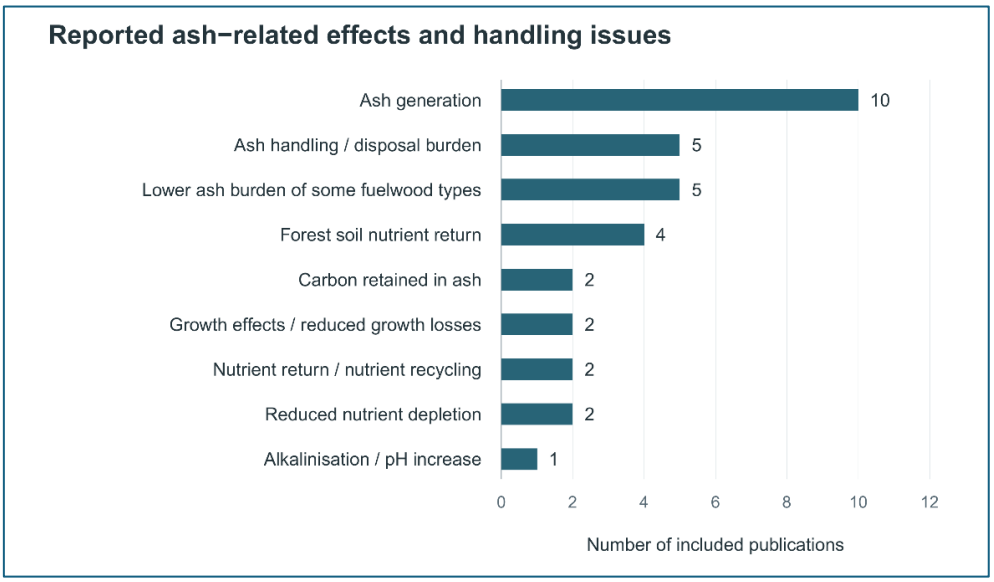


Figure 13. Environmental effects of ash handling identified in the reviewed studies.

A smaller group of studies described the potential beneficial effects of wood-ash recycling, especially as a measure to compensate for nutrient removal after intensive biomass or residue extraction [17,58,65]. Wood ash can return base cations and plant nutrients such as potassium, magnesium, calcium, and phosphorus to forest soils, thereby partly compensating for nutrient removal associated with intensive biomass or harvest-residue extraction and helping reduce soil acidification [17]. These effects may support tree growth on nutrient-poor or acidified sites, although responses are site-specific and depend on ash dose, ash quality, soil properties, stand type, and the balance between nutrient benefits and potential contamination risks. However, the evidence also indicates uncertainty, particularly regarding effects on soil organisms, possible contamination risks, and site-specific soil responses, although some soil faunal groups, such as enchytraeids

and microarthropods, appear relatively tolerant of ash-induced changes in soil chemistry [17].

One study also measured carbon retained in ash after combustion. It found that only 1.1 kg C remained in ash after burning 1000 kg of firewood, meaning that ash retained only a very small fraction of the original wood carbon, while approximately 99.7% of the wood carbon was released during combustion, mainly as CO_2 [41]. This suggests that, under the assessed combustion conditions, ash was not an important carbon-retention pathway in ordinary firewood combustion.

Overall, the evidence shows that ash handling is mostly treated as a minor or secondary issue in the reviewed literature. The dominant finding is not that ash handling causes strong environmental harm, but rather that ash generation, disposal burdens, and possible nutrient recycling benefits are often mentioned without detailed quantitative assessment. Therefore, the environmental implications of ash handling require further detailed examination, particularly regarding ash-disposal pathways, safe recycling to forest soils, nutrient-return benefits, and site-specific soil and ecological responses.

3.6.6. Effects on Carbon Cycle

The reviewed studies addressed carbon cycle effects more frequently than most other environmental-impact categories. As shown in Figure 14, the dominant effects were fossil fuel substitution and net GHG balance improvement, each reported in more than 60 studies. This indicates that much of the literature frames fuelwood use in terms of its potential climate mitigation role, especially when wood replaces coal, oil, natural gas, or other fossil energy sources. The underlying assumption is often that fuelwood belongs to a closed biogenic carbon cycle: carbon released during combustion can be reabsorbed through forest regrowth, while additional climate benefits may arise when wood energy substitutes fossil fuels and thereby avoids fossil carbon emissions. In this context, Schulze et al. [10] argue that the human-induced carbon cycle in managed forests differs from the natural forest carbon cycle mainly because harvested wood can substitute fossil energy. Under sustainable management, managed forests may therefore contribute to climate mitigation through both forest stock increments and energy substitution, whereas unmanaged forests contribute mainly through stock increase, which tends to approach zero over the long term. This perspective also emphasizes that sustainable harvest should not be treated equivalently to deforestation because the former can maintain forest regrowth and substitution effects, while the latter implies a loss of forest carbon stocks and future sequestration capacity.

At the same time, the reviewed evidence shows that the climate effects of fuelwood are not treated as uniformly positive. A substantial number of studies also reported net GHG balance worsening, GHG emissions from combustion, and biogenic carbon neutrality assumption uncertainty [40,68,69,92]. This reflects a central tension in the literature: fuelwood is often considered renewable and potentially carbon neutral, but this assumption strongly depends on forest regrowth, harvesting intensity, combustion efficiency, alternative land use, and the time horizon of assessment. Several studies questioned simple carbon-neutrality assumptions because carbon is released immediately during combustion, whereas forest regrowth and carbon re-sequestration may occur only gradually, and may not occur at all if biomass extraction is followed by conversion to another land use or a permanent reduction in forest carbon stocks [40,58,60,93–95]. Therefore, the reviewed evidence suggests that the carbon cycle effect of fuelwood cannot be assessed only at the point of combustion, but must be evaluated across the full harvest–combustion–regrowth system. In light of short-term climate targets, the issue of timing is particularly important: Lecocq et al. [60] show that policies supporting carbon storage in standing forests may deliver stronger near-term carbon benefits than policies subsidizing substitution of fossil

fuels by fuelwood because substitution benefits may not be sufficient to compensate for losses in forest carbon stocks over policy-relevant time horizons.

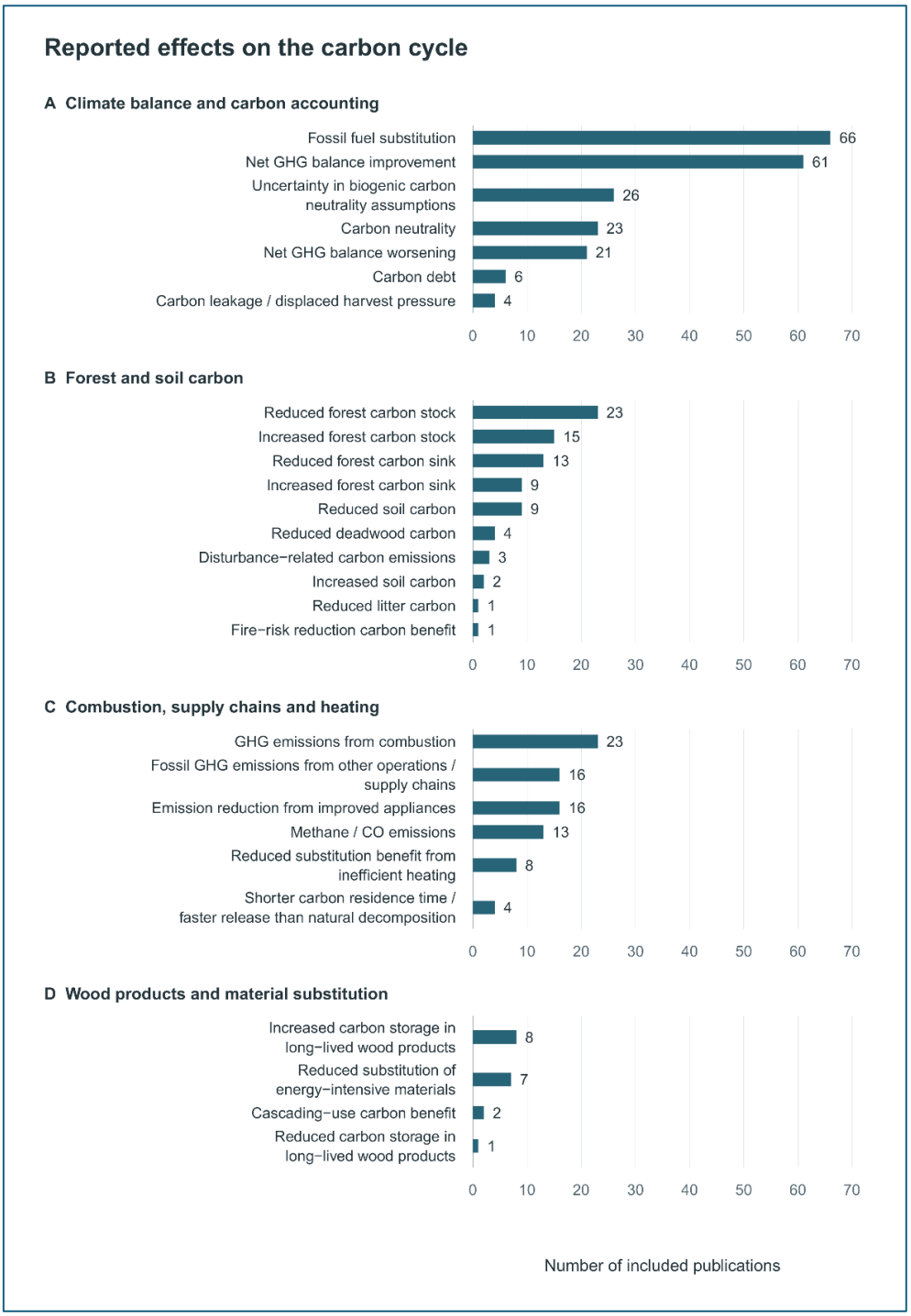


Figure 14. Effects of fuelwood systems on the carbon cycle according to the reviewed studies.

On-site forest carbon stock effects were another important group of reported impacts. The reviewed studies showed contrasting outcomes, including reduced or increased forest carbon stocks and sinks, indicating that the forest-level carbon effect of fuelwood extraction is highly context dependent. Negative effects were generally associated with increased biomass removal, reduced standing biomass, lower inputs to deadwood, litter, and soil carbon pools, or shortened carbon residence time, as combustion releases carbon immediately instead of allowing gradual release through natural deadwood

decomposition [10,49,58,64,76,93]. In contrast, positive or neutral effects were more likely where fuelwood came from residues, low-quality assortments, salvage material, thinnings, or management systems that maintained forest productivity and regeneration [49,51,65,96,97].

A smaller but relevant group of studies addressed carbon storage trade-offs between fuelwood use, long-term carbon storage in harvested wood products, and material substitution effects associated with long-lived wood products [19,45,56,92,93]. These studies indicate that the carbon cycle effect of fuelwood strongly depends on how harvested biomass is allocated between energy and material uses. If wood that could otherwise enter long-lived products is burned, carbon storage in harvested wood products may decline and potential material substitution benefits may be reduced. In contrast, when fuelwood is produced from residues, by-products, low-quality assortments, post-consumer wood waste, or material unsuitable for long-lived products, it may complement wood product pathways without substantially reducing long-term carbon storage and material substitution effects. Thus, the carbon effect not only depends on the sustainability of forest management and the success of forest regrowth, but also on whether fuelwood competes with, or is additional to, higher-value material uses.

Fossil GHG emissions from supply chain activities and reduced energy substitution benefits due to inefficient heating were identified in a notable number of studies [22,23,42,48,63,71,72,98]. These categories highlight that the carbon performance of fuelwood not only depends on the sustainable origin of the fuel, but also on combustion technology, fuel moisture content, logistics, processing, and end-use efficiency. Inefficient stoves or boilers can undermine the potential substitution benefit by increasing incomplete combustion emissions and requiring more wood to deliver the same amount of useful heat compared with fossil fuel alternatives. Similarly, transport, harvesting, drying, chipping, pelletizing, and other supply chain operations can add fossil GHG emissions.

Overall, the reviewed studies show that fuelwood can provide strong climate benefits only under specific conditions: biomass must be sourced sustainably, forest carbon stocks and regrowth must be maintained, combustion technologies must be efficient, supply chain emissions must remain limited, and fuelwood use must not divert biomass from higher-value, long-lived wood product pathways.

3.7. Poverty-Related Problems

Forty-nine publications reported at least one issue relating to household air pollution, obsolete heating technology or poverty-related constraints [23,31,34,37,41,62–64,87]. The reviewed evidence indicates that the environmental and health effects of fuelwood use are strongly connected to poverty-related constraints and obsolete heating technologies. As shown in Figure 15, the most frequently reported issues include particulate matter emissions, public health impacts, indoor air pollution, low combustion efficiency, obsolete heating appliances, appliance maloperation, energy poverty, low income, and dependence on fuelwood. These findings suggest that fuelwood-related household air pollution is not only a consequence of the chemical characteristics of wood combustion and the technological limits of emission reduction in wood-burning appliances, but is also shaped by the socioeconomic conditions under which fuelwood is obtained, stored, and used.

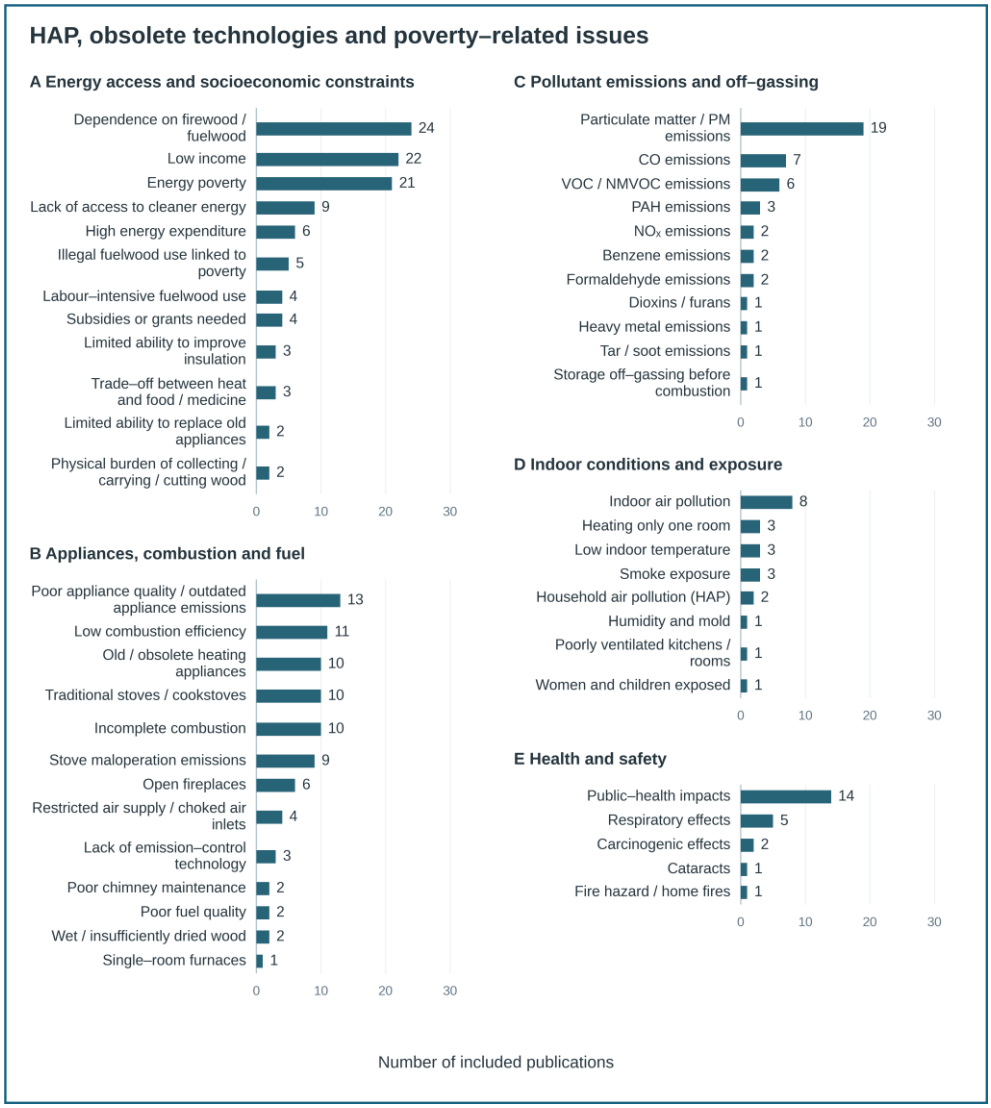


Figure 15. Effects of fuelwood use and obsolete technology use on household air pollution (HAP), together with poverty-related drivers reported in the reviewed studies.

A central pattern in the reviewed literature is that poverty can reinforce inefficient and polluting fuelwood use. The evidence suggests a poverty-trap mechanism in which limited financial resources increase dependence on firewood and prevent improvements in heating systems, while inefficient combustion and poor housing conditions increase fuel demand, pollution, and health risks. The chain of effects that contribute to a generally wasteful utilization of firewood in a situation of poverty is summarized in Figure 16.

Under conditions of poverty, households may rely on fuelwood because of the following reasons: (1) It is more accessible than other energy sources such as coal, natural gas, and grid electricity. The potential for illegal access is also a factor to consider. (2) Its combustion technology is simple and more affordable compared to other energy sources. (3) It can be mixed with household and other easily collectible flammable waste. In the context of extreme poverty, the practice of illegal logging can result in deforestation and the emergence of social tensions. The substitution of firewood with household waste can generate hazardous pollutants, particularly when plastic is involved.

Low income constrains fuelwood users' ability to invest in more efficient combustion technologies or to introduce alternative heating options. Combustion efficiency is further reduced by the fact that the firewood used is damp, as they cannot afford to purchase it several years in advance to allow it to dry properly. The loss of combustion efficiency

contributes to an increase in pollution. The insufficient insulation of their buildings results in a wasteful use of energy. These unfavorable heating conditions mentioned above lead to increased firewood demand and use, which directly increases both pollution and CO_2 emissions and increases the pressure to burn more waste and/or illegal logging.

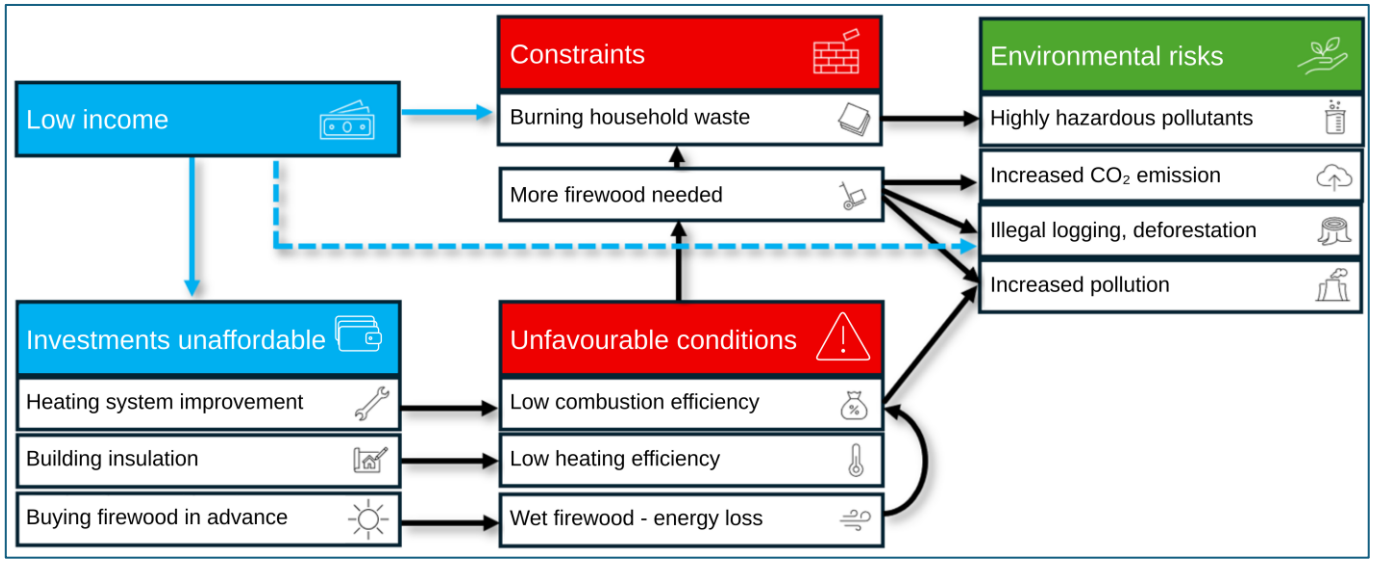


Figure 16. Factors of poverty trap contributing to firewood-related environmental risks.

3.8. The Role of Wood in Energy Transition

The reviewed studies show a clear dominance of energy transition pathways oriented towards wood fuels (Figure 17). Of the 101 reviewed studies, the large majority interpreted energy transition as a shift towards wood-based fuels [40,47,65], while only a small number described transition pathways towards non-wood fuels [35,37,58,63,76,99]. This pattern indicates that, within the reviewed fuelwood literature, energy transition is not primarily framed as the abandonment of wood energy. Instead, wood fuels are often positioned as part of the transition itself, especially in relation to renewable energy targets, fossil fuel substitution, energy security, and carbon-neutrality objectives.

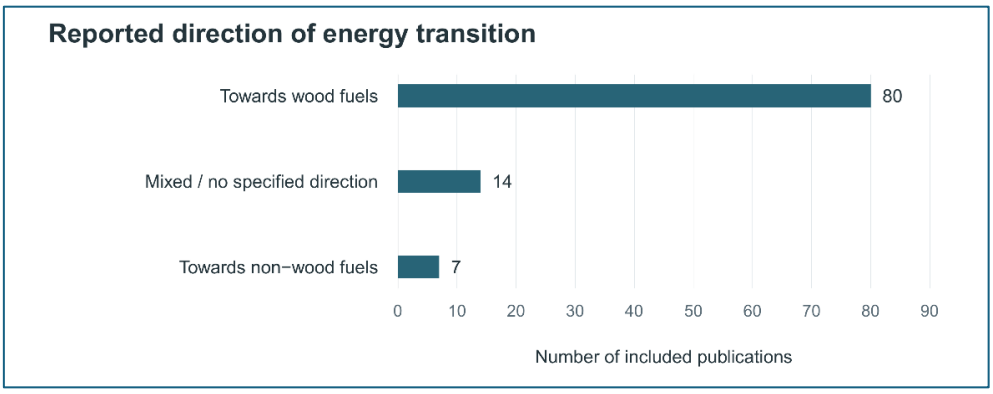


Figure 17. Direction of energy transition reported in the reviewed studies.

Figure 18 shows that the dominant energy transition themes were bioenergy transition, sustainable biomass supply, renewable energy transition, decarbonization, fossil fuel phase-out, and energy diversification, positioning fuelwood within broader shifts towards low-carbon energy systems.

Non-poverty contexts more often emphasized strategic, system-level objectives, including energy security. Poverty-related contexts also addressed these themes, but placed

greater emphasis on household improvements, including energy efficiency, electrification, transitions away from solid fuels, cleaner combustion, improved appliances and fuel quality, thermal retrofitting, user practices, and energy poverty reduction. This suggests that, where poverty is relevant, energy transition is framed both as reducing traditional solid fuel dependence and as improving the socioeconomic, technological, and fuel quality conditions of fuelwood access and use, without necessarily replacing wood entirely.

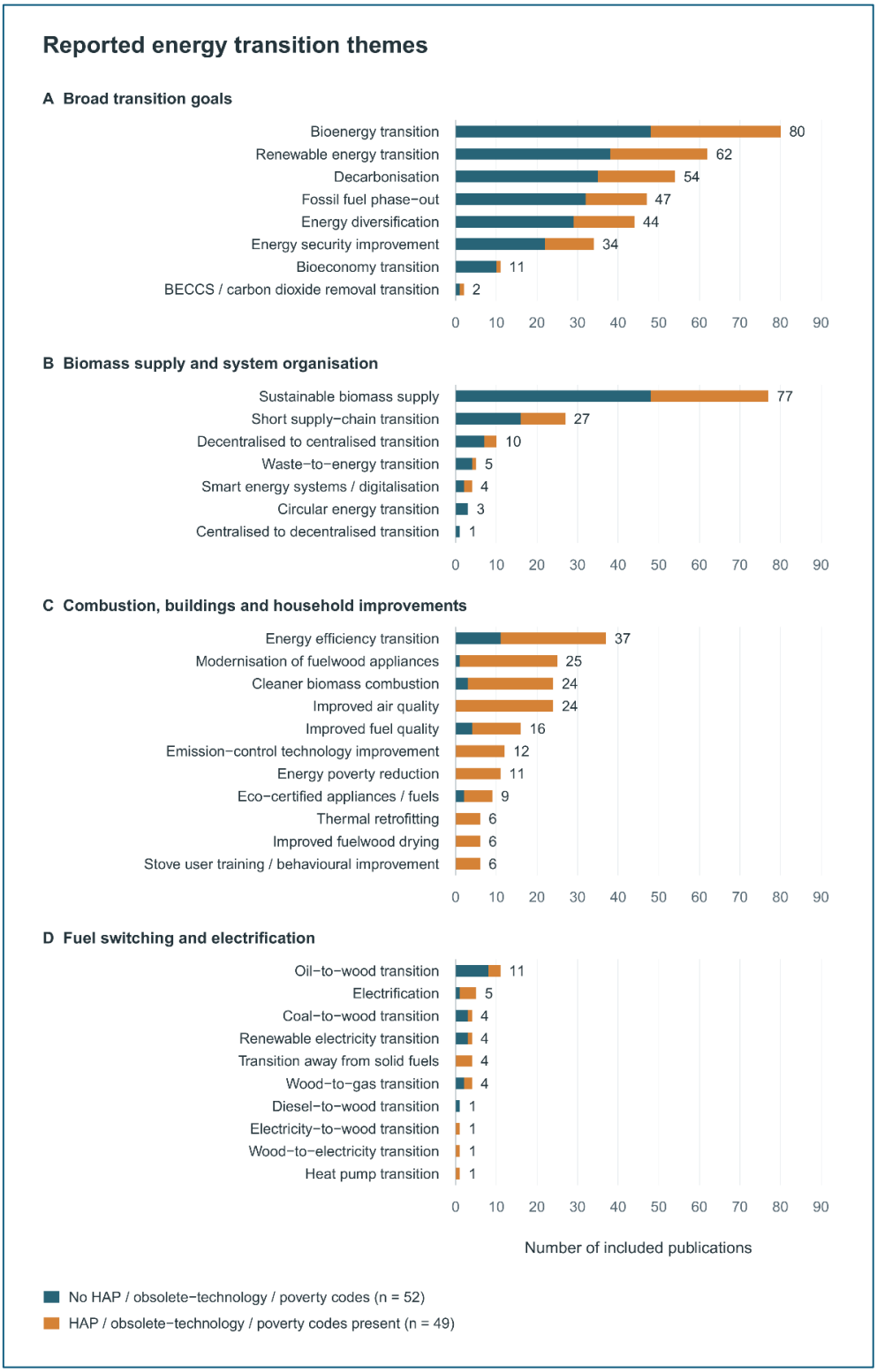


Figure 18. Energy transition categories identified in the reviewed studies, separated by poverty context.

Figure 19 summarizes the interpretation emerging from the reviewed evidence. In the energy transition literature, a common underlying principle is the replacement of inefficient combustion technologies and heating systems, as well as the avoidance of energy sources that inherently involve high environmental impacts [1,28,87]. This serves as a shared starting point for much of the research in this field. The principle is particularly relevant to the burning of household waste, which is often regarded as an indicator of multiple social and environmental disadvantages as it is closely linked to energy poverty, inefficient heating technologies, and the emission of highly hazardous air pollutants [2,63,100]. A similar, although somewhat less severe, case is coal. While coal is generally considered preferable to household waste, it still belongs to a clearly undesirable category of fuels and therefore represents one of the typical starting points for energy transition strategies [25,91].

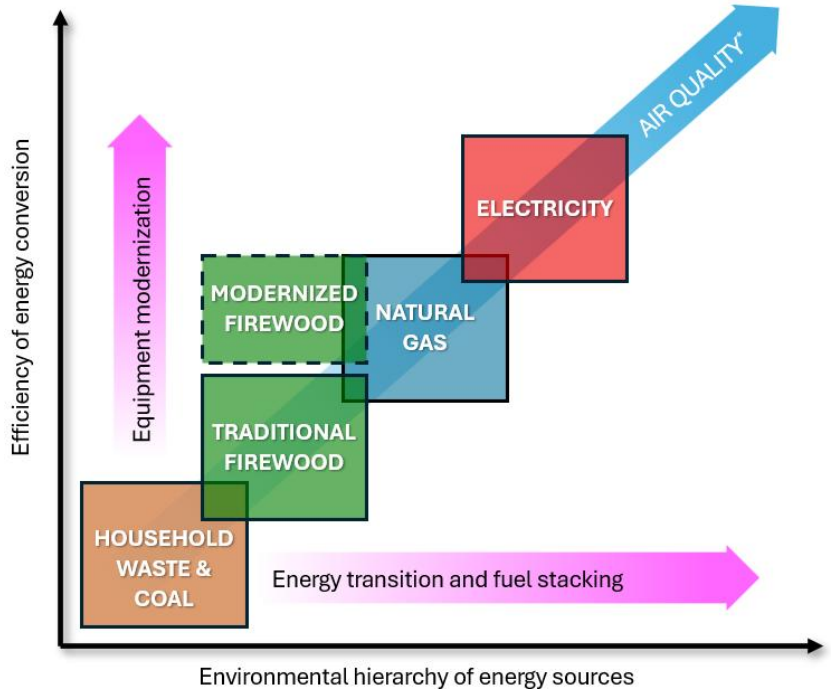


Figure 19. Application of the energy transition and fuel stacking functional framework for our study. * Air quality in the immediate environment of utilization. Carbon cycle effects are not considered.

While the starting point described above is broadly shared across the energy transition literature, its direction and its ultimate goals become considerably more diverse thereafter [61,87]. Natural gas and electrification provide higher energy conversion efficiency and reduced local air pollution [2,30,70,87]. As a result, the literature largely treats these benefits as self-evident and instead concentrates on the technological, infrastructural, and institutional requirements for their effective deployment [63,87].

Compared with the options discussed above, wood occupies a more nuanced position in the energy transition literature. On the one hand, the use of wood in inefficient combustion technologies is frequently considered alongside coal and household waste, placing it among the fuels that the transition seeks to phase out [28,87]. This is especially evident where concerns extend beyond local air pollution to include the environmental risks associated with timber harvesting and forest depletion [17,64,101]. On the other hand, when decarbonization and the replacement of fossil fuels with renewable energy sources are explicitly included among the objectives of the energy transition, sustainably

sourced biomass may be regarded as part of the solution, particularly when used in modern, high-efficiency combustion technologies [1,10,22,28].

Energy stacking is another phenomenon frequently addressed in the literature, in which wood occupies a prominent position [29,33,102]. As a traditional fuel, fuelwood often constitutes the starting point of the energy transition and may continue to be used even after the introduction of additional energy sources, either in its original form or through more advanced combustion technologies [33,63,87,102]. Whether such developments are viewed favorably or unfavorably depends largely on the technological level at which fuelwood use persists and on the relative importance assigned to the three main objectives of the energy transition: improving energy efficiency, reducing environmental impacts, and achieving decarbonization [30,32,39].

The pathway illustrated in Figure 19 is shaped by several facilitating and limiting factors (Table 2). The reviewed evidence suggests that energy transition can not only be hindered by the technical properties of fuels and appliances, but also by infrastructure, affordability, market conditions, policy incentives, household behavior, and lifestyle expectations. These factors help explain why households may remain dependent on traditional fuelwood heating, combine several fuels through fuel stacking, or only gradually move towards cleaner and more modern energy systems.

Key barriers include limited access to energy infrastructure, unaffordable energy sources, unstable or unreliable supply, market price fluctuations, high investment costs for building insulation and new heating technologies, insufficient policy support, and behavioral or cultural attachment to existing heating practices. Conversely, transition can be facilitated by infrastructure that enables connection to alternative energy sources, such as natural gas pipelines, electricity grids, district heating, or decentralized renewable systems. Policy measures, including financial subsidies, renovation support, and appliance-replacement programs, can further reduce the cost barriers associated with cleaner heating technologies.

Table 2. Factors facilitating or hindering energy transition in household heating systems.

Factors		Facilitator	Barrier
Awareness	The level of understanding about the significance of energy consumption in achieving environmental sustainability.	Increased awareness of environmental and health impacts can support cleaner heating choices.	Low income status correlates with low education and environmental awareness.
Attitudes and lifestyle	A person's inner disposition and fixed behavior toward a given topic.	Growing demand for comfort (rising living standard and ageing).	Originality of (rural) lifestyle.
Appliances and building	The technological condition of heating appliances and the energy performance of buildings.	Modern appliances, thermal retrofitting, improved insulation, and cleaner combustion technologies.	Obsolete buildings. Investments required are low or negative return.
Affordability	The ability of households to pay for preferred fuels, appliances, renovation, and connection costs.	Subsidies, low-interest loans, reduced connection costs, and affordable certified fuels.	Preferred energy sources or modern heating technologies may be unaffordable.
Accessibility	The availability of centralized energy supply.	Mass participation can reduce unit costs.	Grid stability problems. Repurposing existing heating and energy systems may involve technical constraints and high costs.
Adverse market and policy environment	Centralized energy supply increases user dependency on market forces and policies.	Multiple heating modes increase flexibility of adaptation.	Fear of price fluctuation and supply insecurity.

Policy	Policies that can influence energy transition.	Social equality increase Pricing externalities.	Insufficient incentives, poorly targeted subsidies, weak regulation of low-quality fuels or obsolete appliances.

4. Limitations of the Review

The review included English-language publications identified through Web of Science and supplementary manual searching. Reliance on one database, title-field requirements, and geographical search terms may have omitted relevant evidence, while the predominance of European studies limits transferability. The review was not registered, and no separate protocol was prepared. Screening and extraction were not performed independently in duplicate, although uncertain decisions and classifications were discussed by the author team. No formal assessment of methodological quality, risk of bias, reporting bias, or evidence certainty was undertaken, and publication counts were not weighted by study quality.

Differences in study designs, wood fuel definitions, technologies, outcomes, comparators, system boundaries and time horizons limited comparability. Extraction focused on thematic categories, and no pooled effect estimates were calculated. Uneven coverage of supply chain stages constrained integrated comparisons. Publication counts describe reporting frequency without establishing effect magnitude, causality or scientific consensus. Overlap between included reviews and primary studies may also reduce evidence independence.

Coding categories were non-mutually exclusive and sometimes conceptually overlapping, limiting comparisons of their frequencies. The combined mixed/no clear judgment category did not distinguish mixed efficiency findings from insufficient information, further limiting interpretation.

The focus on wood-based fuels may partly explain the predominance of publications describing transitions towards wood energy; this pattern does not establish their prevalence or superiority in the wider energy sector. Limited comparisons with alternative heating technologies constrain conclusions about relative environmental, health and socioeconomic performance. Recommendations for modernization therefore remain context dependent and concern improvements where wood remains in use; the review does not establish that modernization is generally preferable to switching to other heating technologies.

5. Conclusions and Implications

This review synthesized 101 publications to organize environmental, health and socioeconomic evidence concerning different wood-based fuels, technologies and supply chain stages. Its contribution is to bring these perspectives together and clarify the conditions affecting their interpretation. The findings support the following conclusions:

1. **Sustainability depends on production and use conditions:** The reviewed literature describes potential contributions to climate mitigation, fossil fuel substitution, renewable energy goals, and energy diversification, alongside forest disturbance, biodiversity loss, air pollution, health risks, and forest carbon losses. Relevant conditions extend from biomass sourcing and transport to combustion, ash handling, and socioeconomic circumstances. Renewable origin alone is therefore insufficient to establish sustainability.
2. **Climate benefits and material-use trade-offs require contextual assessment:** Outcomes depend on forest stocks and regrowth, processing and transport burdens, conversion efficiency, alternative biomass uses, the energy source displaced, and the

assessment period. Burning wood suitable for long-lived products may forgo carbon storage and material substitution benefits. Higher-value material uses and cascading pathways should therefore be prioritized where feasible.

3. **Poverty and obsolete technologies can reinforce inefficient and polluting use:** The reviewed literature links limited household resources and inadequate heating conditions with damp fuel, inefficient combustion, high fuel demand, waste burning, illegal logging and household air pollution. These relationships support addressing fuel quality, appliances, housing, and affordability together. Measures should reduce combustion emissions and household exposure to wood smoke through suitable fuels and correct operation. Appliance modernization alone should not be assumed to eliminate health risks.
4. **Energy transition involves several possible pathways:** Energy transition involves multiple pathways shaped by socioeconomic conditions and priorities for efficiency, pollution reduction, and decarbonization. Inefficient wood combustion may be targeted for replacement, while sustainably sourced wood used in efficient technologies may contribute to transition objectives. Poverty-related contexts additionally emphasize affordability and improvements in household heating conditions. Fuel switching, modernization and fuel stacking therefore require contextual assessment; the wood-focused evidence base does not establish the general superiority of any pathway.
5. **Modernization remains a priority where wood continues to be used:** Relevant measures include sustainable sourcing, efficient and appropriately short supply chains, suitable fuel quality and moisture, modern appliances, improved combustion control and better-insulated buildings. Appliance replacement, fuel-quality standards, user training and building renovation can support these improvements. Their overall benefits should be assessed alongside forest carbon effects, local air pollution and alternative heating options.
6. **Policy priorities should reflect local resources and development conditions:** Where infrastructure and household resources constrain access to cleaner heating, priorities include affordable energy services, social support, and improvements to existing systems. Environmental requirements should avoid imposing additional financial burdens on vulnerable households. In established wood energy markets, priorities include fuel-quality assurance, emission control, and safeguards against illegal logging, household waste burning, and biodiversity loss. Where alternatives are accessible, modern wood-based systems, heat pumps, district heating, and other locally available heating options should be compared in terms of energy sources, costs, and emissions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/resources15120158/s1. Supplementary Material S1: Complete Search Strategy; Supplementary Material S2: PRISMA 2020 checklist; Supplementary Material S3: Data extraction table.

Author Contributions: Conceptualization, E.S.; methodology, É.K. and E.S.; validation, E.S.; formal analysis, E.S., É.K., R.H. and K.R.-E.; writing—original draft preparation, É.K. and E.S.; writing—review and editing, E.S., R.H. and K.R.-E.; visualization, E.S. and É.K.; supervision, E.S.; project administration, E.S. All authors have read and agreed to the published version of the manuscript.

Funding: This article was made in the framework of the project TKP2021-NKTA-43, which has been implemented with the support provided by the Ministry of Science and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

Data Availability Statement: Data is contained within the article.

https://doi.org/10.3390/resources15120158

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Overview of the reviewed studies and the coded fuelwood-related dimensions reported in each study, including country, evidence type, energy transition direction, fuelwood product type, energy production equipment, environmental effects, carbon cycle effects, and poverty-related problems. "X" indicates that the respective aspect was reported or discussed in the study.

Study	Country	Type of evidence	Energy transition aspects	Fuelwood product type reported	Large-scale energy production equipment reported	Household energy production equipment reported	Environmental effects of tree felling reported	Environmental effects of transportation reported	Environmental effects of combustion reported	Environmental effects of ash handling reported	Carbon cycle effects reported	Poverty-related problems reported
[24]	Greece	Survey	towards wood fuels	X	X	X	X	X			X	X
[34]	Cameroon	Economics	towards wood fuels	X		X	X	X				X
[103]	Scandinavia	Modeling	towards wood fuels	X	X		X	X	X		X	
[49]	Switzerland	Resource potential	towards wood fuels	X	X		X		X		X	
[17]	Europe	Review	towards wood fuels	X	X	X	X	X		X	X	
[64]	Kosovo	Interviews	towards wood fuels	X		X	X	X			X	X
[52]	Latvia	Market analysis	towards wood fuels	X	X	X	X				X	
[50]	Argentina	Survey	towards wood fuels	X		X	X	X	X	X		X
[40]	France	Modeling	towards wood fuels	X	X	X	X	X	X		X	
[94]	Italy	Interviews	mixed	X			X	X			X	
[104]	Bosnia and Herzegovina	Survey	towards wood fuels	X	X	X	X				X	X
[102]	France	Econometrics	towards wood fuels	X		X	X		X		X	X
[1]	Global	Review	towards wood fuels	X	X	X	X		X		X	
[59]	Italy	Case study	towards wood fuels	X	X		X	X			X	
[65]	Sweden	Modeling	towards wood fuels	X			X	X		X	X	
[66]	UK	Interviews	towards wood fuels	X	X	X	X	X	X		X	
[19]	Switzerland	Resource potential	towards wood fuels	X	X		X	X	X		X	
[23]	Serbia	Survey	towards wood fuels	X	X	X			X		X	X
[29]	Serbia	Survey	towards wood fuels	X	X	X			X		X	X
[91]	Serbia	Survey	towards wood fuels	X		X			X	X	X	
[100]	USA	Interviews	towards wood fuels	X		X		X			X	X
[70]	Turkey	Resource potential	towards wood fuels	X	X	X	X	X	X	X	X	X
[54]	South Africa	Survey	mixed	X		X	X	X	X			X
[67]	Sweden	Modeling	towards wood fuels	X	X		X				X	
[98]	Switzerland	Economics	towards wood fuels	X	X	X			X		X	X
[105]	Sweden	Review	towards wood fuels	X	X	X	X		X	X	X	
[14]	Global	Market analysis	towards wood fuels	X	X	X	X				X	

[47]	Finland	Interviews	towards wood fuels	X	X	X	X		X		X		
[92]	Global	Market analysis	towards wood fuels	X			X				X		
[51]	Romania	Economics	towards wood fuels	X		X	X				X		
[76]	Spain	Market analysis	towards non-wood fuels	X	X	X	X	X			X	X	
[68]	Global	Modeling	towards wood fuels	X	X	X	X				X		
[96]	Turkey	Econometrics	mixed	X		X					X	X	
[106]	USA	Case study	towards wood fuels	X	X			X	X		X		
[95]	Europe	Econometrics	towards non-wood fuels	X	X		X				X		
[107]	Greece	Econometrics	towards wood fuels	X		X					X		
[55]	Greece	Economics	towards wood fuels	X	X	X	X		X		X	X	
[60]	France	Modeling	mixed	X	X		X		X		X		
[108]	UK	Resource potential	towards wood fuels	X	X			X	X		X	X	
[109]	Norway	Survey	towards wood fuels	X		X				X	X	X	
[101]	Vietnam	Econometrics	mixed	X			X	X				X	
[78]	USA	Modeling	towards wood fuels	X		X			X			X	
[43]	USA	Survey	towards wood fuels	X	X	X		X			X		
[57]	Global	Review	towards wood fuels	X	X	X	X	X	X		X		
[13]	Latvia	Market analysis	towards wood fuels	X	X	X					X		
[48]	Italy	LCA	towards wood fuels	X		X	X	X	X	X	X		
[110]	USA	Experiment	mixed	X	X				X				
[45]	Switzerland	Modeling	towards wood fuels	X		X	X		X		X	X	
[111]	USA	Review	towards wood fuels	X	X	X	X		X		X	X	
[53]	Lithuania	Modeling	towards wood fuels	X	X	X	X	X					
[21]	Poland	Resource potential	towards wood fuels	X	X			X	X		X		
[93]	USA	Modeling	towards wood fuels	X			X				X		
[25]	USA	Modeling	towards wood fuels	X	X		X		X		X		
[69]	Zimbabwe	Resource potential	mixed	X	X	X	X	X	X		X	X	
[112]	UK	Experiment	towards wood fuels	X	X				X	X	X	X	
[41]	Hungary	Case study	towards wood fuels	X		X	X		X	X	X	X	
[97]	Italy	Survey	towards wood fuels	X		X	X				X		
[20]	Lithuania	Resource potential	towards wood fuels	X	X	X	X	X	X		X		
[113]	Europe	Review	towards wood fuels	X	X	X		X	X		X		
[86]	Europe	Review	towards wood fuels	X	X	X			X		X	X	
[71]	Italy	LCA	towards wood fuels	X		X		X	X		X	X	
[74]	Finland	Market analysis	towards wood fuels	X	X		X	X	X		X		
[42]	USA	LCA	towards wood fuels	X	X	X		X		X	X		
[114]	Austria	Experiment	mixed	X		X			X		X	X	
[46]	Austria	Experiment	towards wood fuels	X		X			X		X	X	
[115]	Austria	Experiment	mixed	X		X			X	X	X	X	
[27]	Latvia	Economics	towards wood fuels	X	X	X			X		X		
[72]	Spain	Modeling	towards wood fuels	X	X			X			X		
[36]	Turkey	Review	towards wood fuels	X	X	X	X	X	X		X	X	
[87]	Chile	Survey	towards wood fuels	X	X	X	X		X		X	X	
[10]	Central Europe	Review	towards wood fuels	X	X	X	X	X	X		X		
[85]	Europe	Modeling	towards wood fuels	X	X	X	X	X	X		X	X	
[116]	Russia	Market analysis	towards wood fuels	X	X	X		X	X		X		
[33]	India	Economics	towards wood fuels	X		X	X		X		X	X	
[117]	Sweden	Experiment	towards wood fuels	X	X				X		X		
[77]	North America	Review	mixed	X		X		X					
[61]	Ukraine	Interviews	towards wood fuels	X	X	X	X	X	X		X	X	
[44]	Sweden	Experiment	towards wood fuels	X	X	X			X		X	X	

[63]	Europe	Interviews	towards non-wood fuels	X		X	X	X	X		X	X
[26]	Germany	Resource potential	towards wood fuels	X	X	X	X				X	
[79]	Austria	Experiment	towards wood fuels	X		X			X			X
[118]	Poland	Case study	towards wood fuels	X	X			X				
[119]	Finland	Modeling	mixed	X	X			X				
[56]	Switzerland	Modeling	towards wood fuels	X	X		X				X	
[2]	Global	Review	mixed	X	X	X	X	X	X		X	X
[39]	Slovenia	LCA	towards wood fuels	X	X	X		X	X	X	X	X
[35]	Turkey	Survey	towards non-wood fuels	X		X	X	X	X			X
[99]	Turkey	Survey	towards non-wood fuels	X	X	X	X	X				X
[37]	Turkey	Survey	towards non-wood fuels	X		X	X					X
[22]	Italy	LCA	towards wood fuels	X	X		X	X	X		X	
[73]	Europe	LCA	towards wood fuels	X	X	X	X	X	X		X	
[62]	Chile	Survey	towards wood fuels	X		X	X		X		X	X
[75]	Italy	Case study	towards wood fuels	X	X			X	X		X	
[31]	USA	Experiment	mixed	X		X			X			X
[58]	Sweden	Modeling	towards non-wood fuels	X			X		X	X	X	
[30]	Germany	LCA	towards wood fuels	X	X	X	X	X	X	X	X	X
[28]	Germany	Modeling	towards wood fuels	X	X	X			X		X	X
[32]	Germany	Experiment	towards wood fuels	X		X			X		X	X
[120]	Global	Review	mixed	X	X	X		X	X	X	X	X
[38]	Greece	Econometrics	towards wood fuels	X		X	X				X	
[121]	Germany	Experiment	towards wood fuels	X		X			X		X	X

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