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Evaluating life cycle greenhouse gas emissions from alternative forest residue utilization: Energy and product pathways

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ABSTRACT

This study quantifies the greenhouse gas (GHG) emission profiles of various forest residue utilization alternatives through a cradle-to-grave Life cycle assessment (LCA). Unlike previous studies which were limited in scope, focusing mainly on energy use of residues, there is need for comparative assessments of different alternatives with wider scope. This study compares cradle-to-grave GHG emissions associated with utilizing forest residues for six energy and non-energy applications: electricity, briquettes, sustainable aviation fuel, particleboard, biochar, and mulch. These options of utilizing forest residues were selected based on one or more of the following reasons: easier to implement technologies, processing near the forest, longer-term carbon storage potential, higher economic value, and higher avoided emissions benefit from substitution. The findings suggest that five out of six alternative forest residue utilizations have a lower global warming impact than the given amount of residue burned in piles (from 15 % less for sustainable aviation fuel to 345 % less for biochar). The findings provide critical insights for decision making on forest residues management, fostering a diversified market for forest residue as well as reducing wildfire risk, and maximizing GHG emissions mitigation potential of forests beyond current conditions.

1. Introduction

According to a 2024 report from World Meteorological Organization, there is an 80 % chance that the average annual temperature will exceed 1.5 °C warming between 2024 and 2028 [1]. Alternatives to consuming fossil fuels are becoming increasingly important for limiting global warming. Forests could help mitigate the effects of global warming on the environment, but their ability to do so depends on their management practices [2,3]. Forest management activities such as thinning and harvesting produce a significant amount of residual woody biomass, referred to as forest residues hereafter, which must be managed to mitigate wildfire risk, enhance soil fertility, maintain wildlife habitat, and promote a market for its value-added use. However, in the absence of developed markets and due to high cost of collection, processing and transportation, the common practice is to leave the forest residues in piles close to the harvesting sites [4,5]. Although leaving a fraction of forest residue is necessary to replenish soil nutrients and to support regeneration, the accumulation of large quantities on the forest floor especially under drier climatic conditions like those in western United States pose a potential fire risk. To alleviate such fire risk, the forest residues are often disposed of by open burning in piles or broadcast burning across a defined area. This practice of burning forest residue instantaneously emits stored carbon without any economic use [6]. The negative effects of air pollutants emitted from these open burnings on air quality and respiratory health have been acknowledged in several studies [7–10]. The latest Billion-Ton report estimates near-term biomass availability in U.S. forests at approximately 18.5 million dry tons per year from logging residues and 3.1 million dry tons per year from small-diameter trees, primarily produced by thinning, at shadow price of $40 and $70 per ton, respectively [11]. A shadow price determines the total costs of acquiring the residues and is typically assigned to materials which are not traded commonly in the market.

Even though common understanding suggests that forest residues could be used for energy while generating employment, several factors restrict their use, including accessibility and consistent availability of feedstocks at competitive prices [12–14]. There have been some efforts in assessing the technical feasibility of using forest residues in a various ways [15–17] and financial feasibility of delivering forest residues to

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their use locations [12,15,18,19]. Compared to clean wood chips, forest residues have greater content of bark. In addition, forest residues tend to have more dirt and mineral debris from tree felling and handling in the forest [20,21]. Literature indicates that around 60 %–70 % of the generated forest residues could be utilized for a variety of purposes [17,22]. However, the prevailing market for these residues is restricted to power plants. The market for forest residues needs to be expanded by prioritizing alternatives that can increase their economic value [14] in addition to providing additional carbon benefits by replacing fossil-intensive products and storing carbon for longer period [14,23,24]. Studies have shown the economic potential of using improved technologies to produce new wood products with small diameter timber generated from thinnings depending on their size and physical characteristics [3,25,26]. Other uses such as making briquettes [27,28], wood products like oriented strandboard and particleboards (Cabiyo et al., 2020; Pedzik et al., 2022), biochar or mulch for soil application [29,30], and transportation fuels for aviation [31] could create additional revenue streams and opportunities for a diversified market for forest residues utilization [15]. Considering the wide variety of alternatives for using forest residues, this study aims to quantify their greenhouse gas (GHG) emission profiles for a given amount, enabling a consistent comparison. Life cycle assessment (LCA) has been commonly used to estimate the potential environmental impacts of energy uses of forest residues. However, as mentioned above, most of the previous studies were limited in scope, focusing mainly on single use of residues. There is a need for comparative assessment of different alternatives with broader scope.

Two key research questions addressed in this study are: 1) What are the life-cycle greenhouse gas emissions associated with alternative approaches to utilizing forest residues? 2) How different forest residue utilization alternatives compare for a given amount of forest residue. To address these research questions, this study estimates the cradle-to-grave GHG emissions associated with utilization of forest residues for six energy and non-energy products. Among the alternatives evaluated in this study are production of electricity, briquettes, sustainable aviation fuel, particleboard, biochar, and mulch. These options of utilizing forest residues were selected based on one or more of the following reasons: easier to implement technologies, positive market outlook, possible production near the forest, longer period of carbon storage, higher economic value, and substitution benefits. The information on the life cycle GHG emissions and potential substitution benefits of different forest residue use options would support decision-making when a comparison between different equivalent alternatives is required. The outcomes could contribute towards the development of diversified forest residue markets as well as reducing wildfire risk and maximizing GHG emissions mitigation potential of forests beyond the status quo.

2. Methodology

The study followed the LCA methodology guided by ISO standards 14040 and 14044 in estimating the GHG emission profile of alternative utilization of forest residue. The process of LCA for different forest residue utilizations alternatives followed steps of goal and scope definition, selection of functional unit, delineation of system boundary, life cycle inventory, and impact assessment as structured through following sections.

2.1. Goal and scope definition

The goal of the study was to assess the cradle-to-grave GHG emissions profile of six forest residue utilization alternatives: electricity, briquettes (torrefied and non-torrefied), sustainable aviation fuel, particleboard, biochar, and mulch. Although the study was not geographically specific, most of the methodology choices and inventory data were obtained from studies involving forest residue utilization in the western United States.

2.2. Functional unit

Since forest residue uses selected in this study serve different functions, an input based functional unit was selected. All inputs and environmental impacts are referenced to a functional unit of one oven-dried (OD) kilogram of forest residues that is considered available for recovery and use. Currently, 65 % of the forest residues generated are left onsite for pile burning and the remaining fraction (35 %) is assumed to decompose naturally [17].

2.3. Definition of system boundaries

The definition of the system boundary determines which parts of the system will be included in the analysis to achieve the study's goal. The system boundaries for all forest residue utilization alternatives (Fig. 1) began with residue recovery and preprocessing activities like loading, unloading, screening and grinding, followed by transportation to the use location. The activities related to upstream forest management operations were not included in the study since the use of forest residues would not influence them. Forest residues were assumed to be air dried for one year before collection, and they have a moisture content between 17 % and 23 % [14,32]. Air-dried forest residues are ground before hauling to the use sites. Past studies have supported pre-processing near the landing site instead of transporting loose forest residues for collection and processing [33,34].

The forest residues utilization for electricity includes direct combustion of woody biomass in a boiler and utilizes a steam cycle to produce electricity (Fig. 1a). A 20 MW bioelectricity power plant was assumed at an average hauling distance of 100 km to receive forest residues. The amount of forest residue needed for 1 kWh electricity was 1.134 oven dried kg. This information was generated using data from a study by Xu and colleagues where 119,204 tonne/year (dry basis) feedstock generated 105,120 MWh annual electricity [35]. The generated electricity was considered to displace equivalent amount from U.S. national electricity mix for year 2022 at 0.375 kg CO_2/kWh.

Fig. 1b and c presents cradle-to-grave system boundaries for two types of briquettes manufactured from forest residues near the forest. Forest residue feedstocks (air-dried and chipped) were transported an average distance of 18.8 km from the primary landing to use location for briquette manufacturing [36]. Briquette manufacturing from forest residues was considered for two type of briquettes, non-torrefied and torrefied, to be used in two alternative uses: generating thermal energy for residential heating and producing electricity by co-firing at a coal-fired power plant, respectively. After manufacturing, the non-torrefied briquettes were packaged, stored, distributed 90 km distance, and burned in a wood stove at 72 % efficiency. Torrefied briquettes were assumed to be transported longer distance of 211 km for use in power plant [27].

Fig. 1d showed system boundary for utilization of forest residues in production of aviation fuel (SAF) which can displace conventional jet fuel in aircraft. The life cycle GHG emissions have been estimated for different routes of SAF production based on forest residues [31,37–39]. In this scenario, SAF was produced via gasification followed by Fischer-Tropsch catalysis as described by Ahire and colleagues [31]. Transport distance from forest residues landing to SAF producing plant was assumed as 100 miles (161 km). The plant capacity considered was 90 Mg SAF per day requiring 960 Mg feedstock used at 30 % moisture, giving a mass yield of 9.4 % with nearly 2 % mass yield of renewable diesel. The SAF produced has lower heating value 43 MJ/kg [40,41]. The SAF produced was assumed to be transported to 640 km for end use in a jet engine. As SAF and conventional jet fuel have the same properties for use in a jet engine, the combustion emissions were assumed to be the same [40].

Another use of forest residue, specifically small-diameter trees from thinning, was considered in manufacturing of particleboard (Fig. 1e), a non-structured panel that is used as component in making furniture,

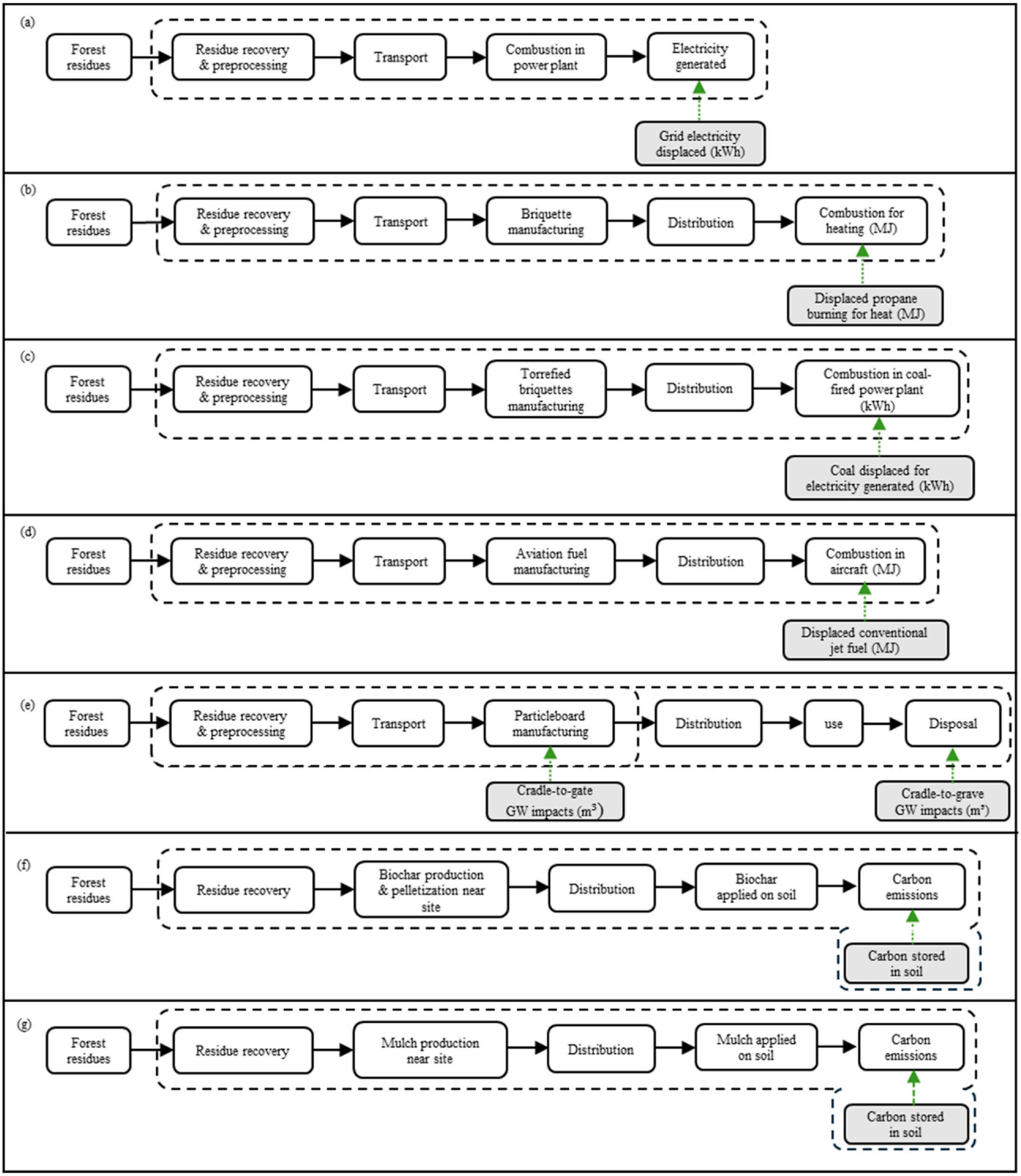

Fig. 1. Definition of cradle-to-grave system boundaries in forest residue utilization alternatives: (a) electricity (b) non-torrefied briquettes (c) torrefied briquettes (d) aviation fuel (e) particleboard (f) biochar and (g) mulch. Gray color boxes with dotted arrow in green color only show the location where in the life cycle the GW impacts were estimated, displacement factors were estimated, or carbon was stored in soil permanently. Although not shown in the figure, each system boundary includes inputs of material and energy as well as outputs of emissions and waste.

cabinets etc. The use of forest residues for particleboard production was assumed to expand the supply of wood (e.g., mill residues) for the manufacture of engineered wood products [42,43]. The data was more representative up to the manufacturing stage and more assumptions needed for the LCI of downstream processes, the LCA of particleboard was conducted at two system boundaries: cradle-to-gate and cradle-to-grave. However, no substitution was applied because particleboards go into various end-uses like furniture which was beyond the scope of this analysis.

Biochar was produced in a mobile biochar-producing air curtain burner near the site of slash piles (Fig. 1f). Pelletization of biochar was included for better handling and application to soil. The substitution of biochar for equivalent nutrients in chemical fertilizers was not included because of the uncertainty of several indirect effects [44]. Yet, the study included the benefits of carbon stored in the soil from the applied biochar. Of the carbon contained in biochar, a 90 % recalcitrant fraction is estimated to remain in soil for more than 100 years compared to 10 % labile carbon pool [45]. Mulch production from forest residues was a simple grinding process followed by application on the landscape (Fig. 1g). The carbon in mulch (50 %) applied on land was assumed to have 9.7 % recalcitrant fraction modelled as sequestered and the remaining gets emitted by decomposition in the first year [46]. For both mulch and biochar applications, the fractions of carbon emitted and the carbon fraction that remains stored for over 100 years were included in their GHG emissions profiles. For similar reasons as with biochar, the substitution benefits of mulch were not considered in this study, since mulch is usually applied as a soil amendment. Additional details on the life cycle stages of biochar and mulch production and application are available in the supporting information.

2.4. Life cycle inventory (LCI) data

The baseline scenario in this study considered leaving 65 % of forest residues onsite for pile burning and remaining 35 % for natural decomposition. The GHG emissions from burning forest residues (Table 1) were based on data from a field study conducted by Aurell and colleagues in 2017 [7]. The GHG emissions (kg/kg biomass) from pile burning of forest residues were 1.689 kg CO_2 and 0.0057 kg CH_4. Since the CO_2 emitted from burning was biogenic in origin, it was not included in the analysis, but CH_4 emissions were counted as an anthropogenic GHG. The natural decomposition fraction was assumed to remain unchanged in all scenarios and hence was not included in the analysis. For the forest residue utilization alternatives, cradle-to-grave GHG emissions inventories for life stages were compiled for this study. Most of the methodological choices and LCI data were obtained from studies involving forest residue utilization in the western United States (supporting information provide more details). The choices on some LCI aspects such as transportation distances and selected manufacturing process were guided by studies showing near forest site operations and easier to implement technologies. Further, the LCI data for some of the alternatives such as SAF production was based on lab-scale process simulation rather than actual commercial operations. This was noted as a limitation that changes in the LCI parameters could affect the results in any forest residue utilization alternative; however, no sensitivity analysis for the individual alternative was conducted to verify this. Furthermore, sensitivity analyses tend to be conducted for individual products assessed, so they were considered outside the scope of this study [47–49]. More details on LCI data for each alternative and their equivalents identified for substitution benefits are provided in the supporting information (Table S1–S8).

Table 1 shows the substituted equivalents identified for alternative forest residue uses. For each alternative, the supporting information section provides details on LCI data and for their equivalents identified as substitutes. For biochar and mulch produced from forest residues, substitution equivalents were not defined, since they are typically used as amendments to improve soil health and crop productivity, and the substitution equivalency for chemical fertilizers is not 1:1 [39,44]. Nevertheless, the study included the benefits of recalcitrant carbon pool in biochar and mulch that remained stored for more than 100 years. For particleboard, no substitution benefits were assumed based on personal communications with expert from Composite Panel Association, since there was no direct non-wood alternative [61] and end uses like furniture and cabinets were not in the scope of this analysis.

Table 1
LCI data sources for GHG emissions inventory of forest residue utilization alternatives.

Utilization alternative	Output unit	Substituted equivalent	LCI data sources
Electricity	kWh	Grid electricity	[35,36,50,51]
Briquettes	MJ	Propane burned in residential heating	[27,36,52]
Torrefied briquettes	MJ	Coal burned in coal-fired power plants	[27,36,53]
Sustainable aviation fuel	MJ	Conventional Jet fuel	[31,36,54]
Particleboard	m^3	No substitute	[36,55,56]
Biochar	kg	No substitute	[29,36,45,57]
Mulch	kg	No substitute	[36,58–60]

2.5. Impact assessment

The impact assessment phase was aimed at estimating the potential environmental impacts using the LCI data. The impact assessment in this study was conducted for only global warming (GW) impacts quantified using U.S. based TRACI method [62] and SimaPro 9.6 software [63]. The global warming impacts were assessed for 100-year time horizon for different uses of 1 OD kg forest residue. The GHG emission profile of each forest utilization alternative was evaluated with contribution analysis of life stages through cradle-to-grave. It is noteworthy that the GW impacts estimated for each alternative are contingent to the LCI data quality and methodological choices within their life cycle stages [49, 64]. Further, the study examined the displacement factors (DFs) related to potential benefits of substituting forest residues for equivalent products. The DF for forest residues substituted product or energy equivalents were estimated based on their GHG emission intensities, by following below expression [65]:

$$DF = \frac{GHG_{nw} - GHG_w}{C_w}$$

Where GHG_{nw} and GHG_w are emissions of GHGs from production and use of non-wood and wood (forest residues in this study) alternatives, respectively, expressed in mass units of carbon equivalent, and C_w is the amount (mass unit) of wood used in wood alternatives, assuming there is no wood in the substituted non-wood product. The carbon content of GHG emissions is calculated as 12/44 CO_2e. The carbon content of forest residues was assumed to be 50 % of OD weight. DF is dimensionless, and a positive DF implies that use of forest residues would reduce the GHG emissions.

3. Results and discussion

3.1. GW impacts and substitution benefits of forest residue uses

The estimated GHG emission profiles of different forest residue utilization alternatives were based on their respective LCAs. Table 2 presents the estimated GW impacts of each alternative normalized to functional unit 1 OD kg forest residue input. The GW impacts of all six alternative forest residue uses were lower than the reference pile burning option, except for particleboard. Biochar and mulch had the

Table 2
Global warming impact of forest residue utilization alternatives along with the displacement factors.

Residue use	GW impact[a] (kg CO_2e/kg residue)	Displacement factor[b] (unitless)
Pile burning	0.143	Reference
Electricity	0.031	0.164
Non-torrefied briquette	0.103	0.386
Torrefied briquette	0.113	0.906
Sustainable aviation fuel	0.121	0.151
Particleboard (cradle-to-gate)	0.288	–
Particleboard (cradle-to-grave)	0.386	–
Biochar	−0.350	–
Mulch	−0.124	–

[a] A negative GW impact indicates that the alternative forest residue uses results in a net reduction of GHG emissions rather than contributing to them.
[b] A positive displacement factor indicates that forest residue-based products or energy displaces more GHG emissions than it generates, suggesting an overall benefit in terms of reducing GHG emissions.

lowest GW impact followed by electricity generation. The biochar use of residues was found most beneficial (a negative GW impact) because around 90 % of the recalcitrant carbon in biochar remains stored for more than 100 years. Mulch's GW impact was also negative because of the little processing involved in manufacturing and nearly 10 % recalcitrant carbon fraction of mulch. The use of forest residues in making wood products such as particleboard, despite its high GW impact, could be justified by its long-term carbon storage; 1 m^3 particleboard stores 1123 kg CO_2 carbon delaying its release for its reference service life of 75 year [55]. Additionally, manufacture of particleboard from forest residues would make more woody biomass available from conventional mills into the wood industry sector for the manufacture of additional particleboards or other wood-based panels.

The DF of forest residue uses were estimated to quantify the avoided GHG emissions when they substitute non-wood alternatives for equivalent functions. The estimated DFs (Table 2) were based on the GHG emission intensity of a forest residue alternative compared to its fossil-based alternative identified in methodology section 2.4. Since the change in residue uses was not considered marginal for this analysis, the calculated DF should be interpreted as an efficiency of avoiding GHG emissions for a specific residue use rather than as GHG emissions mitigation efficiency. The positive DFs in all applications indicate potential substitutable carbon benefits of using the residues instead of pile burning. The highest DF observed for two briquette types is mainly attributable to using simple conversion technologies combined with shorter transportation distances. Since briquette manufacturing uses low quality biomass, they can be a promising alternative for forest residue utilizations. After briquettes, the highest DF was observed for electricity generation and aviation fuel production, both of which are supported by existing policy initiatives [35,37]. The lack of previous studies comparing the environmental impacts of these different alternatives of using forest residues through an LCA highlights the importance of the study.

3.2. Contribution analysis of forest residue utilization alternatives

3.2.1. Electricity

The analysis showed using forest residues to generate electricity caused GW impact of 0.037 kg CO_2e/kWh. The electricity generated can substitute for grid electricity. The GW impacts of forest residue generated electricity were found to be about 91 % lower than those of U.S. average grid electricity (0.375 kg CO_2e/kWh), and 78 % lower than pile burning the same amount of forest residues required to generate 1 kWh electricity. The potential reduction in GW impacts were similar to those reported in other studies on using forest residues to generate electricity [35]. Regarding the contribution of life stages in total GW impact (Fig. 2), electricity generation process and transportation distance had the largest influence at about 58 % and 31 %, respectively, followed by residue recovery process.

For the hauling of forest residues to power plant facility, truck transportation over an average distance of 100 km was considered in this study, but the total GW impacts would vary with change in distance as indicated in previous studies [35]. Increased distance would cause more fuel consumption and subsequent emissions influencing GW impact. The study by Xu and colleagues (2021) evaluated regional variations in the GHG emission reduction potential of different low-value forest biomass feedstocks and found a high reduction in emissions ranging from 86 % to 93 % relative to U.S. average grid electricity emissions of year 2019 [35]. Since about 61 % of the electricity generated in 2022 in U.S. was from fossil fuels [51]; using forest residues for electricity generation can reduce the percent share of fossil fuels for electricity generation. Therefore, using forest residues to generate electricity could contribute significantly to reducing GHG emissions for electric power generated in U.S. along with the prevention of air emissions and health impacts of pile burning and reducing the catastrophic wildfire risks.

3.2.2. Briquettes

Fig. 3a and b shows the percentage share of life stages in cradle-to-grave GW impacts of non-torrefied (NTB) and torrefied briquettes (TB) produced from forest residues. Compared to pile burning, using forest residue to make NTB and TB had 28 % and 21 % less GW impacts per kg residue input, respectively. NTB manufacturing assumed field (air) drying and densification of low-quality forest residues near the site of residue generation, which showed GHG emission benefits when combusted in a wood stove for residential heating. The GW impacts per MJ heat produced by NTB were 87 % lower than those of propane fuel. For 1 MJ heat, cradle-to-grave GW impacts of propane fuel were 0.063 kg CO_2e as compared to 0.008 kg CO_2e/MJ NTB. Torrefaction of briquettes improved their physical properties (Table S2). The TB substituting coal in coal-fired power plants had GW impacts of 0.020 kg CO_2e/MJ, which was 94 % less as compared to 0.309 kg CO_2e/MJ of coal.

As evident in Fig. 3, the manufacturing process contributed most to life cycle GW impacts of both briquette types. Although relatively small, the transportation of briquettes contributed second most to total GW impacts after manufacturing. The aggregated contribution of transportation stages (transport of forest residues and distribution of briquettes) indicates a potential trade-off for stakeholders for balancing environmental and economic concerns. The TB was projected to be transported even farther than the 211 km considered in this study, which could likely increase the total GW impact. Overall, since briquette manufacturing allows use of low quality biomass, they can become an attractive utilization alternative for forest residues. The LCA results suggested that the use of forest residues for briquette manufacturing could contribute significantly to reducing GHG emissions while also reducing the quantity of residues burned in piles.

3.2.3. Sustainable aviation fuel

The sustainable aviation fuel (SAF) production from forest residues considered gasification based Fischer Tropsch pathway with integrated power generation unit. The SAF yield per kg dry biomass was 13 % [31]. The cradle-to-grave LCA results of SAF production from forest residues showed a GW impact of 0.026 kg CO_2e/MJ. For 1 OD kg residue input, SAF production had 15 % lower GW impact compared to pile burning. Furthermore, the substitution benefits for a 1 MJ of SAF translated to a 70 % reduction in GHG emissions as compared to conventional jet fuel (0.084 kg CO_2e/MJ) and hence an opportunity for reducing the carbon intensity of aviation sector. Similar reductions has been reported in previous studies on SAF production [37,39]. Akter and colleagues reported similar carbon savings for SAF production from logging residues via ethanol-to-jet pathway (70.6 %) and Iso-Butanol-to-jet pathway

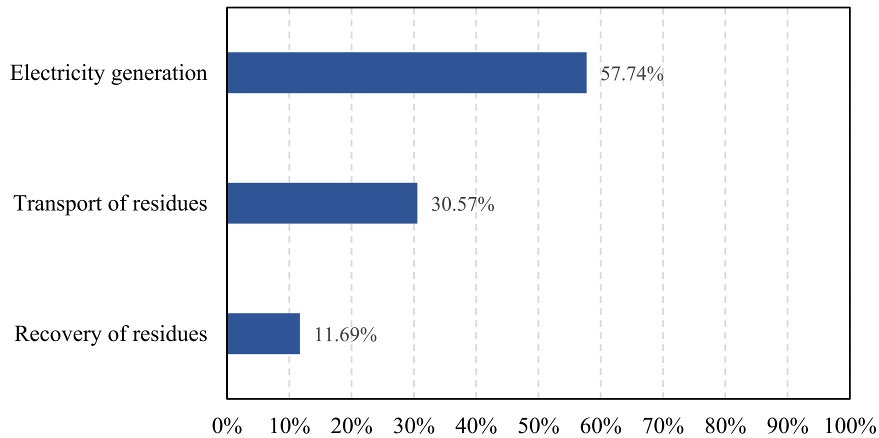

Fig. 2. Percentage contribution of cradle-to-grave life stages in total GW impacts of forest residue generated electricity (0.037 kg CO_2e/kWh).

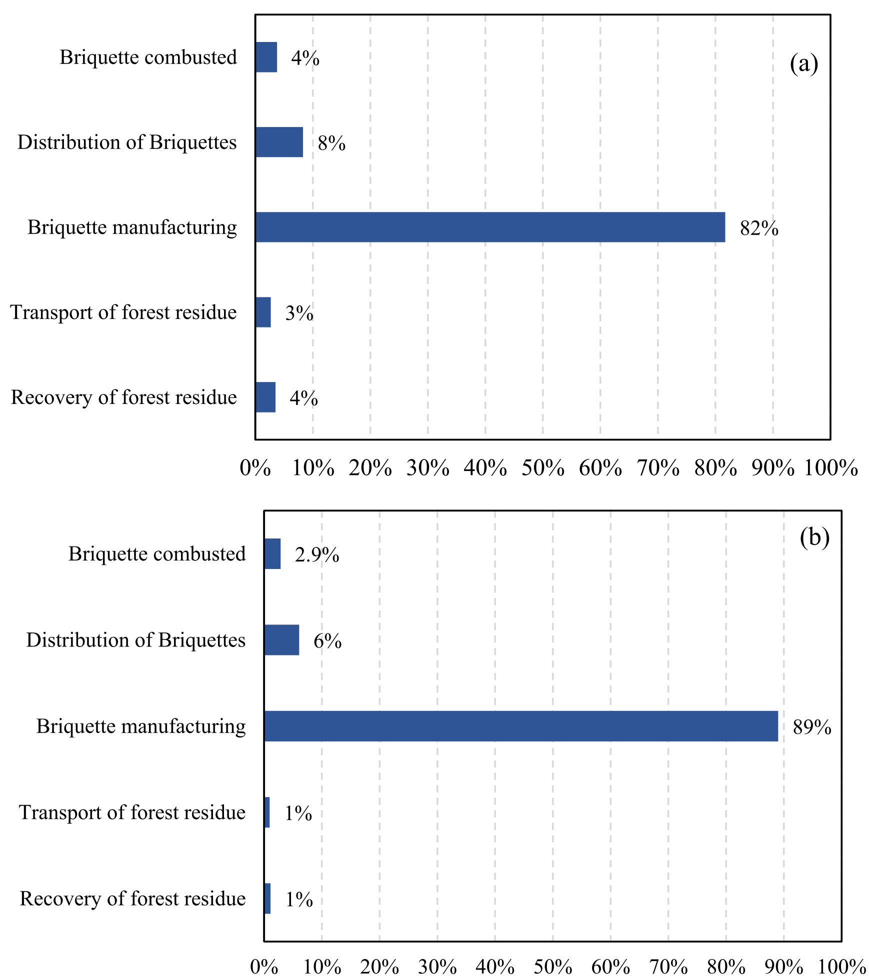

Fig. 3. Percent contribution of cradle-to-grave life stages in GW impacts of (a) non-torrefied briquettes (0.008 kg CO_2e/MJ) and (b) torrefied briquettes (0.020 kg CO_2e/MJ).

(62.1 %) as compared to conventional jet fuel [37]. A percentage contribution of cradle-to-grave life stages to total GW impacts of SAF (Fig. 4) showed manufacturing process as the most influential variable. It was noted that various assumption in process design specific to selected conversion process could affect the estimated GW impacts. Since production of SAF can generate tax credits ($0.33/L) for a 50 % or more reduction in GHG emissions compared to conventional jet fuel, additional feedstocks from forest residues would represent a great opportunity for SAF producers in U.S [37]. Several airlines aiming to replace 10 % of conventional jet fuel with SAF by 2030 underlines the importance of utilizing forest residues for SAF production [66].

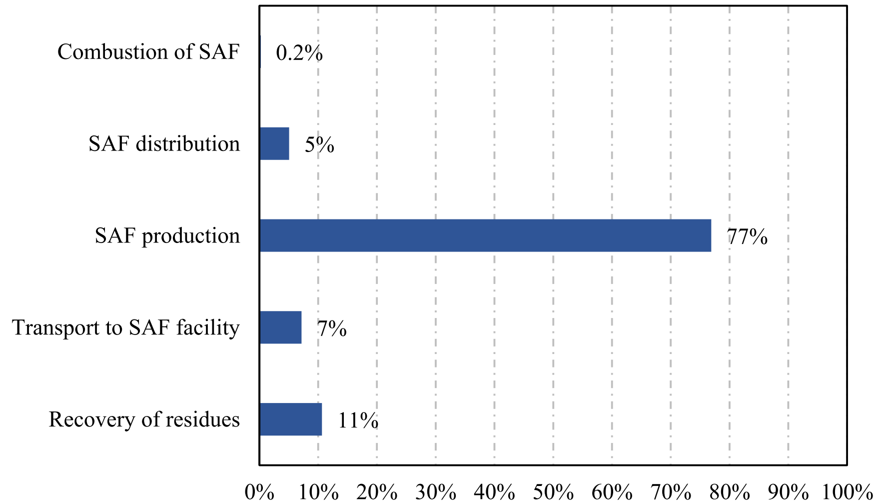

Fig. 4. Percent share of cradle-to-grave life stages in GW impacts of sustainable aviation fuel production from forest residues (0.026 kg CO_2e/MJ).

3.2.4. Particleboard

Using forest residues to manufacture wood products such as particleboard could be a useful value-addition that not only reduces pile burning emissions, but also potentially substitute for non-wood alternatives while delaying the release of stored carbon. For forest residues based-particleboard, the GW impacts were assessed at both cradle-to-gate and cradle-to-grave system boundaries, since the latter is more influenced by the methodological choices (S5). Fig. 5a and b shows the percent share of life stages in cradle-to-gate and cradle-to-grave GW impacts of particleboard, respectively. For a total cradle-to-gate GW impacts of 181 kg CO_2e/m^3, the major contributor was particleboard manufacturing process followed by extraction of non-wood raw

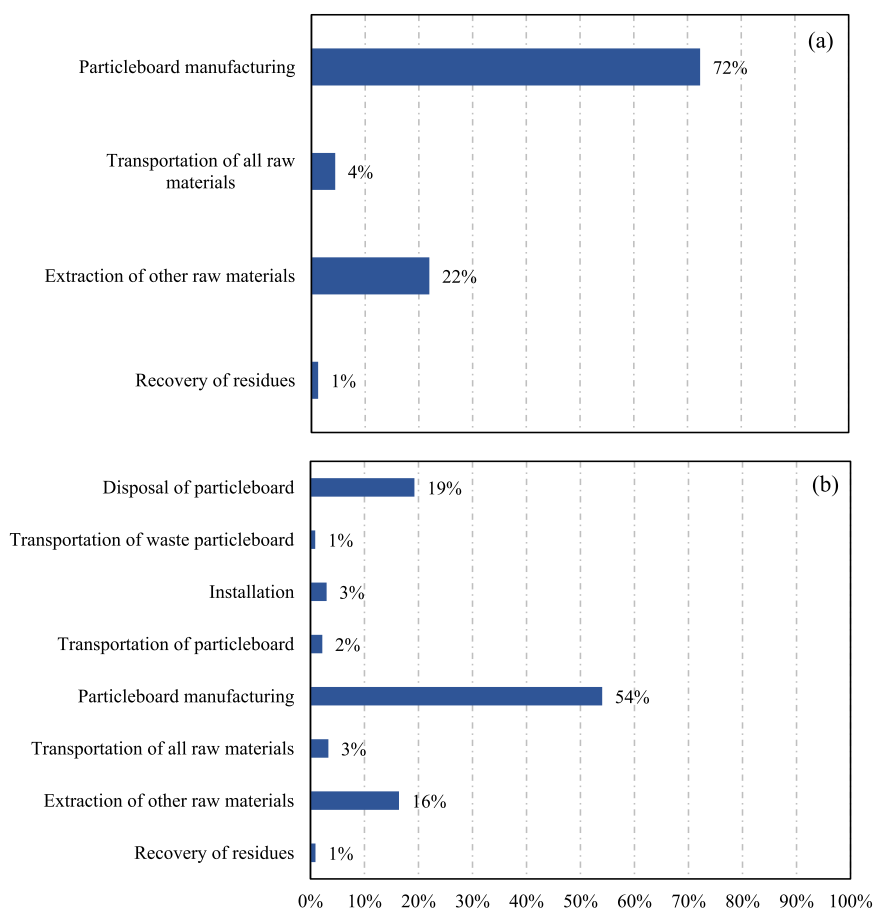

Fig. 5. Percent contribution of life stages in GW impacts of particleboard for (a) cradle-to-gate system boundary (181 kg CO_2e/m^3) and (b) cradle-to-grave system boundary (243 kg CO_2e/m^3).

materials such as resins and additives used in manufacturing.

For cradle-to-grave system boundary, the main hotspot was still manufacturing stage (54 %), but the end-of-life disposal caused 19 % of the total 243 kg CO_2e GW impacts per m^3, which can be attributed to the landfill gas emissions assumed without energy capture. Since landfill gas is 50 % methane, which has high GW potential, the impact of particleboard end-of-life disposal can be reduced if fractions of particleboard waste going to landfills are diverted to incineration or recycling. It was noteworthy that the choice of end-of-life disposal method can significantly affect the total GW impact. When comparing the GW impacts with pile burning, the particleboard manufacturing does not appear environment friendly (Table 2), but this use can be justified by the fact that using forest residues for particleboard manufacturing would expand the supply of roundwood for production of more wood products.

3.2.5. Biochar

Based on the LCA results, it was apparent that producing biochar via a mobile pyrolyzing unit near the sites of forest residue piles could be a suitable alternative. The total cradle-to-grave GW impact estimated was −2.03 kg CO_2e/kg biochar, which corresponds to climate benefit while avoiding the pile burning emissions. The negative GW impact indicates that using forest residue for biochar production results in a net reduction of GHG emissions rather than contributing to them. This outcome was mainly attributable to a large proportion of recalcitrant carbon remaining stored in biochar. Fig. 6 shows the percentage share of life stages along with the end-of-life emissions and removals displayed separately for each carbon pool (recalcitrant and labile). Carbon emitted from soil application of biochar and carbon stored there were converted to carbon dioxide (Fig. 6).

Since about 90 % of the biochar carbon was recalcitrant or less reactive in nature, that amount of carbon assumed to remain sequestered permanently on a 100-year time horizon. The biochar production at ~18 % yield from forest residues near the landing sites contributed 9 % of the GW impacts. Transporting the residues to further distances for large scale operations could affect the GW impact. There have been studies showing around 25–35 % biochar yield from wood chips [67] but require studying the trade-offs in GW impacts in more detail [30,67]. Given the size of forestry sector in U.S. and available low-valued forest residues, deployment of mobile pyrolyzing units for biochar production could play a crucial role in sustainable forest management. Studies have shown that the biochar produced from a cost-effective process would be a great source of soil amendment for reclamation of degraded soils and several other applications [68]. To support decision-making for commercial applications where biochar can replace chemical fertilizers in soil or in wastewater treatment, more studies are needed to evaluate environmental and economic trade-offs [69].

3.2.6. Mulch

The cradle-to-grave GW impacts of 1 OD kg mulch produced from forest residues was −0.131 kg CO_2e. Fig. 7 shows percentage contribution of life stages towards the net GW impact. Converting forest residues into mulch was a simple grinding process expected to be near the landing site. The negative GW impact of mulch was mainly attributed to its application on soil. A 9.7 % recalcitrant carbon in mulch was modelled as sequestered, with the remainder labile pool of carbon emitted in the first year of the application. Since mulch (i.e., wood) contains a large fraction of labile carbon, its decomposition led to higher carbon emissions. Yet, the LCA results showed that converting a 1 OD kg forest residue to mulch yielded 187 % lower GW impacts than burning it in a pile (Table 2). Mulch production from forest residues near the landing sites could be an easily implemented utilization strategy. Studies have also shown that a layer of mulch applied on post-fire soils prevent soil fertility loss [70]. Application rate of forest residue mulches could vary from 2.6 to 10 metric tonne per hectare depending on the desired percent of ground cover [70,71].

4. Conclusions

By evaluating the life cycle GHG emissions of various forest residue uses for producing energy and wood products, this study filled the gaps in previous literature, which were focused primarily on a single energy use of residues. Since the U.S. forest sector is large, and low-valued forest residues are available from forest restoration activities to mitigate wildfire risks, alternative utilization instead of pile burning could be implemented for a variety of applications, from those that are quite mainstream (electricity) to those that can be implemented near forests with low capital investments (briquettes, biochar, mulch), as well as some that are more forward-looking and would require substantial capital investments for operating economically (sustainable aviation fuel, particleboard).

For a functional unit of 1 kg OD forest residue used, the analyses showed that all alternative uses showed lower GW impacts compared to conventional pile burning, except for particleboard. Biochar and mulch production were found most beneficial mainly because of their recalcitrant carbon pool that would remain stored for over a century, combined with its simple production process resulting in smaller manufacturing emissions. Next beneficial forest residue use for a given amount was in electricity generation, followed by briquettes and aviation fuel, with particleboard showing higher GW impacts than pile burning. Although substitution benefits of avoided GHG emissions were more evident in briquettes, followed by electricity and aviation fuel, particleboard from forest residues would still delay the release of carbon emissions into the atmosphere until the end of its service life, and increase the availability of wood for other wood product manufacturing (i.e., enhance resource efficiency). Overall, these findings suggest that utilizing forest residues

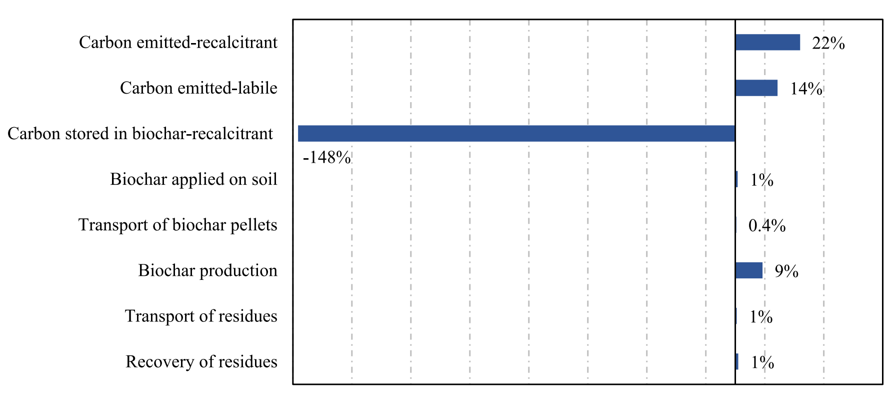

Fig. 6. Percent contribution of cradle-to-grave life stages in GW impacts of biochar production from forest residues near the landing site (−2.03 kg CO_2e/kg).

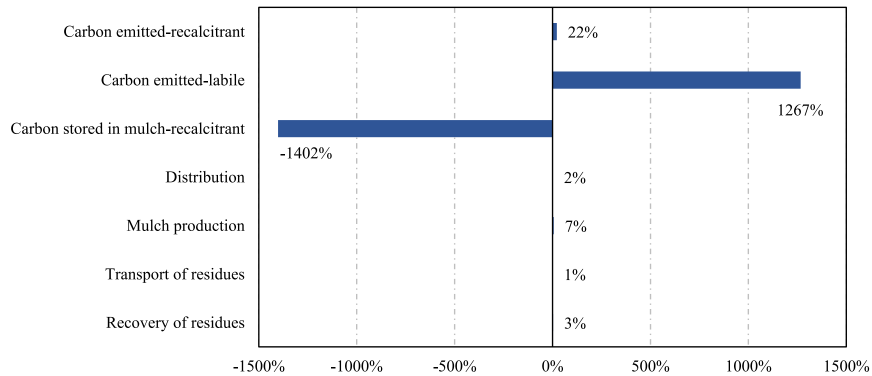

Fig. 7. Percent contribution of cradle-to-grave life stages in GW impacts of mulch produced from forest residues (−0.131 kg CO_2e/kg).

for energy and products instead of the current practice of pile burning can certainly play an important role in reducing GHG emissions, preventing air emissions and health impacts of pile burning, while mitigating the catastrophic wildfire risks.

However, it was noteworthy that these results are contingent on the assumptions related to the life cycle stages. Since transportation of forest residues could be a limiting factor, the LCAs developed for six alternative uses of forest residues assumed production operations within distances of about 100 km from forests. Considering near-woods operations, even lower distances (18.8 km) were used for manufacturing briquettes, biochar and mulch. Further, various assumption specific to selected conversion processes at the manufacturing stage in all alternatives could change the GW impacts. Although no sensitivity analysis was performed to verify, it was noted as a limitation that changes in the LCI parameters could affect the results of the study. For example, the LCI data for SAF production was based on lab-scale simulation rather than actual commercial operations. Several market and policy factors need to be considered when choosing forest residue uses. More studies are needed to evaluate the trade-offs between environmental and economic factors. But a study like this could assist industry and policymakers in developing long-term strategies since there can be multiple uses of forest residues. It is possible to make more informed decisions about investments in wildfire risk mitigation activities by demonstrating which scenario or combination of forest residue uses will provide the greatest carbon benefits.

CRediT authorship contribution statement

Poonam Khatri: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard Bergman:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Prakash Nepal:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **David Nicholls:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **Andrew Gray:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.108059.

Data availability

Data will be made available on request.

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