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Biohydrogen, a potential roadmap to sustainable green energy supply and carbon sequestrating in the transport sector by 2060

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ABSTRACT

Current research goals lead to achieve zero carbon emission in transportation, agricultural, and forest sector through biohydrogen production by biomass residues. To assess the current development status and forecast future technologies, Traffic emission evaluation model of project (TEEMP) was used. Results show that, in 2024 cumulative CO_2 emission by forest and agricultural were 3.5 billion metric tonne (BMt) while from transportation 8.47 BMt. Major assessments indicate that globally about 5–10 Gt/year of biomass residues are technically and economically recoverable, mainly from China, India, the U.S., Russia, and Europe, corresponding to roughly 40–60 EJ/year of bioenergy potential. Instead of burning these wastes in fields, they should be collected, converted into biohydrogen, and used as a fossil fuel replacement to reduce CO_2 emissions. So far, biological pre-treatment and dark-photo fermentation are well-known techniques for the production of high-quality biohydrogen due to their controllability and low energy consumption. The experimental findings showed that the collection of agricultural 1840 Mt and forest 927 Mt waste residues can produce 15,460 Kt and 929 Kt of biohydrogen respectively, which will help to achieve to reduce the carbon emission of 85.13 Mt agriculture and 57.75 Mt forest by 2040 respectively. Sustainable biohydrogen production can be achieved by enhancing the production capacity by solving collection, transportation, and management challenges. These challenges can be overcome through the development of policies, implementations, laws, government and organization training, satellite monitoring, and electronic media. Lastly, bottom-up accounting framework scenario reflected the overall possibilities of CO_2 emissions reduction from 9.699 BMt to 0.03 BMt by 2010 to 2060 can be reduced from the atmosphere by stopping the open field burning of waste residues and using biohydrogen as an alternative to fossil.

1. Introduction

Climate change is a critical global challenge, primarily driven by human activities that release greenhouse gases (GHGs) into the atmosphere, leading to global warming [1]. The main contributors to GHG emissions include the burning of fossil fuels [2], deforestation, agricultural practices [3], and industrial activities. These emissions have far-reaching consequences, including extreme weather events, rising sea levels, ecosystem disruptions, water scarcity, health risks, and socio-economic challenges. Among GHGs, carbon dioxide (CO_2) is the most significant contributor to atmospheric pollution [4], due to its dominant share in anthropogenic emissions, long atmospheric lifetime,

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and central role in global mitigation policies. CO_2 accounts for approximately three-quarters of total GHG emissions and remains in the atmosphere for centuries, making it the primary driver of long-term warming. In contrast, CH_4 and NO_x, though strong in the short term, have shorter lifetimes and are typically regulated through sector-specific measures rather than economy-wide policies [5]. Furthermore, CO_2 emissions are supported by more comprehensive, consistent, and comparable datasets across countries and sectors, enabling robust analysis aligned with the study's objectives.

The burning of fossil fuels for energy production, transportation, agriculture, forestry, and industrial processes is the dominant source of CO_2 emissions [6]. The transportation sector alone accounts for approximately 20 %−23 % of global CO_2 emissions, releasing nearly 7.3 BMt annually [7]. Similarly, the agricultural and deforestation sectors contribute 12 %−15 % of global carbon emissions due to practices such as farming, open-field residue burning and deforestation [8]. According to the World Health Organization (WHO), the overall agricultural food system emits 17.3 BMt with open fields burning 2.78 BMt and wildfires emitting 1.76 BMt of carbon emission [9]. These unsustainable activities further exacerbate climate change, necessitating urgent mitigation strategies. According to projections from NASA, Duke University, and Columbia University, global temperatures could rise by 2.5 °C to 4.5 °C by 2100 unless fossil fuels are replaced with sustainable alternatives [10]. This pressing need to combat climate change has driven extensive research into low-carbon and environmentally friendly energy sources [11].

In response to these challenges, recent studies highlight the critical role of renewable energy such as solar, wind, hydropower, geothermal [12], and bioenergy in replacing fossil fuels as clean or carbon-neutral alternatives [13]. Undoubtedly, all these energies have been extensively contributing in CO_2 reduction since last decade, however it's no enough to meet the energy demand for all industrial, agricultural, and transportation sectors due to extensive growth of economies in the different regions of the world. Among these, biohydrogen has emerged as a promising clean energy alternative, offering significant potential to meet the energy demand and help to decarbonize multiple sectors, including transportation and agriculture [14]. The environmental impact assessment (EIA) agency predicts biohydrogen is a poise potential energy fuel in mid of 21st century that will be utilized widely in numerous sectors of the global economy in the next decades provided that solves all these hurdles which come in its commercialization place [15]. The global energy demand is projected to reach 580 million terajoules annually, consuming approximately 13,865 Mt of petroleum products [16]. However, current hydrogen production is predominantly fossil-fuel-based, with over 95 % of commercial hydrogen derived from coal [17], natural gas, and petroleum products, contributing significantly to GHG emissions [18].

Biohydrogen production from agricultural and forest waste such as biomass residues like cereal crops, and lignocellulosic materials is a smart way to reduce carbon emissions and make good use of leftover materials. Instead of letting this waste decay and release CO_2 into the air [19]. It can be turned into clean energy through processes like digestion, gasification or pyrolysis. This helps cut down pollution and reduces the need for fossil fuels making it a useful step toward a cleaner environment [20]. Global biomass residue generation is estimated at around 140 gigatonne (Gt) per year, with over 60 % originating from low-income countries. This value represents the gross theoretical potential; however, the technically and economically recoverable fraction is considerably lower, typically 5–15 Gt/year, as reported by FAO and IPCC [21].

Forest residues, mainly from developing countries, contribute about 50 % of global forest waste, including materials like stumps, dead wood, and branches [22]. Despite extensive research on biohydrogen production, limited attention has been given to the utilization of agricultural and forest biomass residues as a feedstock for large-scale hydrogen production [23]. These residues, often discarded as waste or burned in open fields represent an untapped resource for biohydrogen production [24]. The inefficient disposal of these residues not only leads to unnecessary carbon emissions but also signifies a lost economic opportunity, particularly for developing regions. The ongoing research and investments in the field could lead to advancements that may eventually facilitate commercialization in the future.

Recent developments in biohydrogen production technologies have significantly advanced process efficiency and yield across various technical routes. Dark fermentation has benefited from lignocellulosic residue pretreatment, co-culture microbial systems, and integration with photo-fermentation, achieving yields up to 7–9 mol H_2/mol hexose. Photo-fermentation improvements, including LED-based targeted illumination and metabolic engineering, have enhanced hydrogen productivity from organic acids [25]. Microbial electrolysis cells have emerged as a complementary route, recovering additional hydrogen from fermentation effluents using low-cost electrodes, while thermochemical processes such as gasification and pyrolysis have been optimized with advanced catalysts and CO_2 sorbent integration to improve syngas quality and H_2 output [26]. Compared with these pathways, residue-based biohydrogen offers distinct advantages in feedstock cost, carbon footprint, and potential integration with rural economies, making it an attractive focus for large-scale, low-carbon hydrogen production.

However, presently biohydrogen production faces several challenges like that hinder its large-scale commercialization. A significant challenge is the inefficient allocation and availably of biomass, along with inadequate infrastructure for collection and transportation, especially in remote areas where logistics can be expensive and impractical. Additionally, there is a lack of awareness among farmers regarding the economic potential of leftover biomass, as well as limited recognition from governments and the private sector about its economic and environmental benefits over other renewable energy options. Regulatory and policy gaps further hinder progress, making it difficult to establish a supportive framework for biohydrogen development and utilization.

This study advances the field by integrating residue-to-hydrogen pathways with quantitative feedstock assessments, situating them within techno-economic and environmental benchmarks against conventional fuels, and embedding them in a policy-informed adoption roadmap. By combining realistic residue availability, system-level comparisons, and TEEMP-based transport projections, the work moves beyond descriptive reviews to provide a strategic framework for mobilizing residues into scalable biohydrogen solutions for transport decarbonization. Furthermore, the novelty of this research lies to address these challenges by developing an integrated framework model that combines multiple theories, methodologies, or systems into a unified structure which will optimizes biomass allocation through data-driven logistics models, enhances infrastructure via decentralized biomass collection and transportation to production units, in-depth analysis of biohydrogen potential application over other renewable energy sources, promotes farmer engagement through digital marketplaces and incentive mechanisms. Lastly, this research will propose policy recommendations to bridge regulatory gaps and foster public-private partnerships, facilitating the transition toward a sustainable hydrogen economy. Lastly, projecting the global potential of biohydrogen in transportation and its carbon reduction scenario by 2060.

Objective of this study to provide a comprehensive evaluation of agricultural and forest biomass residues for biohydrogen production, with a specific focus on its potential contribution to reducing CO_2 emissions in the transportation and agricultural sectors. The study aligns with China's national carbon neutrality plan and the global Paris Agreement targets for 2060 by examining: Annual biomass residue availability and utilization potential across different regions, Efficient collection, management, transportation and conversion strategies for biohydrogen production, Economic viability and scalability of biohydrogen as a green energy solution, Projected CO_2 emission reductions through biohydrogen adoption in the transportation sector. To achieve these objectives, this research introduces an integrated analytical approach combining the TEEMP Model for precise CO_2 emission evaluations. This approach enables a quantitative assessment of biohydrogen's impact on transportation sector emissions under various adoption scenarios filling the critical gap in prior studies.

2. Methodology

2.1. Data collection and parameters

Data on agricultural and forestry-based biomass waste residues were gathered to analyze annual production, collection, and incineration of waste residues. This data collection encompassed composted agricultural waste residue information (in kilograms of dry matter) sourced from published literature (https://data.worldbank.org). Forest residue data was obtained from a published report of the forest resources assessment, detailing the physical quantity of forest waste residues (in kilograms of wet or dry matter) (https://www.fao.org). Additionally, global transportation fuel vehicle and CO_2 emission data from 2001 to 2024 were sourced from the World Bank's website (https://ourworldindata.org/transport). In this study, the carbon footprint of waste biomasses, biohydrogen production, and the associated CO_2 reduction potential were assessed following the ISO 14067:2018 standard, applying a life cycle-based approach as reported in recent literature, which represents the most widely recognized framework [27]. Emission factors were derived from TEEMP model outputs and LCA databases. The whole research scheme and models used in this study has been in Fig. 1.

This study adopts a global perspective on biohydrogen production potential, while incorporating region-specific datasets such as those from China, the European Union, Africa, and the United States as, illustrative case studies. These regional datasets are not analyzed in isolation but are conceptually integrated into the broader global system model to demonstrate how local variations in feedstock availability, infrastructure, and policy can inform and strengthen a global roadmap for sustainable biohydrogen development.

2.2. Agricultural and forest residues analysis

Biomass Utilization Efficiency (BUE) measures how effectively the available biomass is converted into useful products or energy instead of being wasted. It can be calculated using a ratio-based approach as follows Eq. (1)

$$BUE(\%) = \frac{\text{Quantity of biomass effectively utilized}}{\text{Total biomass availabe}} \times 100 \tag{1}$$

Where:

BUE (%): Biomass utilization efficiency in percentage.

Quantity of biomass effectively utilized: Portion of biomass actually collected and used for productive purposes (excluding collection, transport, and processing losses).

Total biomass available: Total physical quantity of biomass residues generated (e.g., in t/year or kg/year).

Future biomass utilization efficiency for energy production is calculated using projected biomass generation and collection rates, derived from historical agricultural and forestry data with consistent system boundaries, conversion factors, residue-to-product ratios (RPR), and collection fractions (Fc) to ensure comparability.

2.2.1. Agricultural residues analysis

The potential amount of biohydrogen generation depends on crop yield and collectible crop residues per years. Eq. (2) illustrates the agricultural residue-based biohydrogen Potential [28,29].

$$H_2 = Y_{H_2}\{F_c(C_P \times RPR - C_a \times F_g \tag{2}$$

Where:

H_2: Potential amount of hydrogen (kg).
Y_{H_2}: Biohydrogen yield (kg H_2 per ton of residue).
F_c: Fraction of collectable residue.
C_p: Crop production (t), "t" mean tone.
RPR: Residue-to-product ratio (dimensionless).
C_a: crop area harvested (ha) mean per hector.
F_g: Ground-use coefficient (t/ha).

The term (Cp × RPR) represents the total theoretical residues

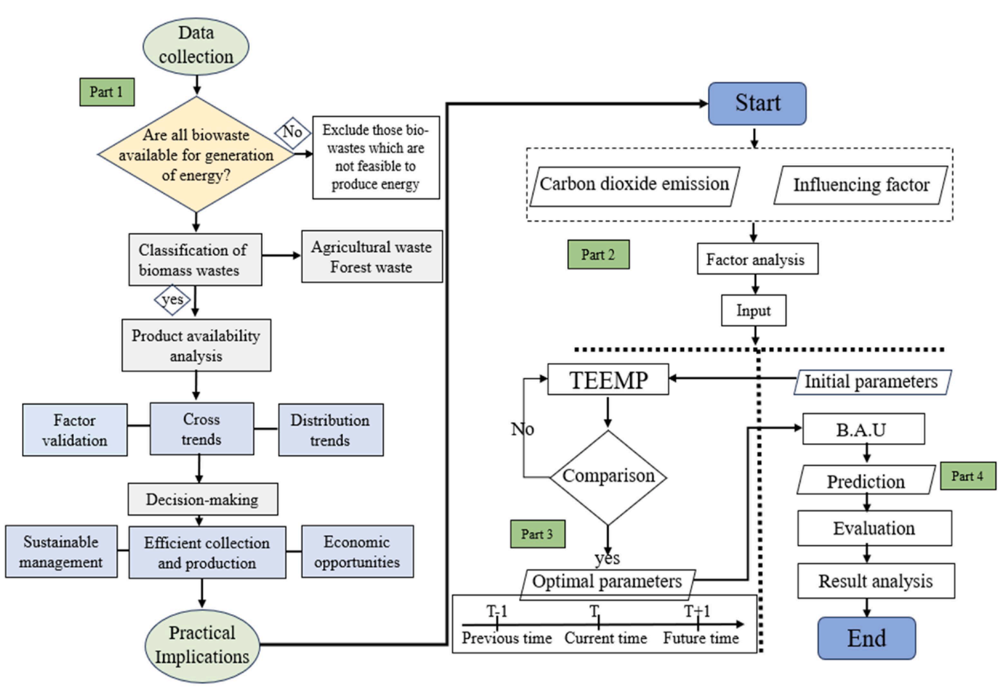

Fig. 1. Framework of biomass residue assessment and TEEMP modeling for biohydrogen production, including data collection, factor analysis, parameter optimization, prediction, and practical implications.

produced, while (Ca × Fg) represents residues left in the field and not collectible. The difference, multiplied by F_c, gives the number of residues available for hydrogen production.

2.2.2. Forest residues analysis

The bio-hydrogen production from forest biomass waste depends on yield and collectible waste residue type [30]. The following Eqs. (3) and (4) illustrate the factor effecting biohydrogen production by forest waste residues:

The waste production (t), and area harvested (ha) are double exponential smoothing forecast

$$H_2 = Y_{H_2}\{F_c(F_P \times RPR - F_a \times F_g \tag{3}$$

For H_2 yield reported as L/kg dry biomass

$$H_2 = Y_{H_2}(F_P \times RPR \times TS\ Content \times Y_P \tag{4}$$

F_P is the worldwide forest generation on a yearly basis (tons/year), F_A: Area harvested (ha), TS content is the total solids content of the raw residue (%) and H_2 is the bio-hydrogen yield of the forest residue (Y_C for raw substrate or Y_P for pre-treated substrate) while (L/kg dry biomass).

2.3. Open field waste residue burning CO_2 emission analysis

The estimation of the total amount of CO_2 emission by burning of agricultural and forest waste residues was calculated by using the subtotal method [31]. The following Eq. (5) illustrates the total carbon emission:

$$Q_{m,i,t} = \sum (P_{m,i,t} \cdot N_i\ .\ B_m \cdot F \cdot EF_i) \tag{5}$$

Where:

$Q_{m,i,t}$: Q is representing the total carbon release (tonnes of carbon), $\sum$ (For all waste residue types), (annual biomass production in tonnes; m, illustrate the individual country of the world. i represent individual waste residue of the all-major residues such as (agriculture: rice, sugarcane, wheat, and corn [32].

Forest residue: branches, needles, leaves, roots, bark, and slabs, etc.), t represents the year. subscriptions, $P_{m,i,t}$is the amount (tonnes) of collected waste residue (dry or wet form) of type i waste residue in country m, N_i is the ratio of grain to straw of the crop type i (the ratio of residue to crop product fraction), B_m is the fraction of waste residue burn in the open field in the country (m). While F is combustion efficiency of waste in the field. EF is the emission factor of gaseous pollutants of waste residue (tonnes of carbon/tonnes of dry matter).

2.4. The TEEMP detailed model

The TEEMP model assesses CO_2 emissions by comparing a baseline fossil fuel scenario with a biohydrogen intervention scenario. Boundary conditions include the geographic and temporal scope, system limits (feedstock collection, transport, biohydrogen production, and vehicle use), technology assumptions, and emission factors. Validation was conducted by comparing model outputs with historical emission data and published literature [33], ensuring consistency and reliability of the results.

The model simulates gradual biohydrogen adoption in transportation, replacing petrol, diesel, and gas. The application assumes that the technological efficiency of biohydrogen-powered vehicles remains stable throughout the projection period. It also requires access to country-specific fuel economy data and detailed vehicle fleet statistics for accurate baseline estimations [34]. Assumptions include stable vehicle efficiency, availability of country-specific fuel economy and fleet data, and constant emission factors unless improved by technology. The Business-as-Usual (BAU) scenario was used as the benchmark in the TEEMP model, providing a reference for precise assessment of current and future emissions projection under biohydrogen adoption. Fig. 1 illustrates the model's structure, this framework facilitates a comprehensive evaluation of global CO_2 emissions from biohydrogen production and use, highlighting significant reduction potential by 2060. For the emission comparison between fossil fuel combustion and biohydrogen in transportation, the TEEMP model employs the following key parameters:

$Fuel_i$: Mass or volume of fuel type iii combusted.
HC_i: Heat content of fuel type i (Energy per mass or volume of fuel).
C_t: Carbon content of fuel type i (Mass of C per unit energy).
FO_i: Fraction of carbon oxidized during combustion.
$CO_2(m.w)$ and C $(m.w)$: Molecular weights of CO_2 and carbon, respectively.

Vehicle activity data.

The energy consumption determines globally or each country's CO_2 emissions from transportation by Eq. (6) [35].

$$\text{Emission} = \sum_{k=0}^{n} Fuel_i \times HC_i \times C_t \times FO_i \times \frac{CO_{2(m.w)}}{C_{(m.w)}} \tag{6}$$

$Fuel_i$ mass or volume of Fuel types i combusted, HC_i, Heat content of fuel type i ($\frac{\text{Energy}}{\text{Mass or volume of fuel}}$), C_i, carbon content of Fuel type i $\frac{\text{MassC}}{\text{energy}}$, FO_i, fraction oxidized of fuel type i, CO_2(m.w) molecular weight of CO_2, C(m.w), molecular weight of carbon.

Eq. (7) calculates total annual fuel consumption from total driving activity and fuel efficiency. Eq. (8) estimates annual CO_2 emissions based on fuel consumption and emissions per kilometer. Eq. (9) calculates the total kilometers driven per year by all vehicles in the system [36].

$$T_{cfpy} = T_{drive}/D_{pl} \tag{7}$$

$$CO_{2epy} = T_{cfpy} \times CO_{2epkm} \tag{8}$$

$$D_{pykm} = T_{nc} \times D_{Apy} \tag{9}$$

Hence,

T_{efpy}: Total fuel consumption per year (liters)
T_{drive}: Total driving activity (e.g., vehicle-km per year)
D_{pl}: Average distance driven per liter of fuel (km/L)
CO_{2epy}: Total CO_2 emissions per year (kg/year)
T_{cfpy}: Total fuel consumption per year (liters)
CO_{2epkm} : CO_2 emissions per kilometer (kg/km).
D_{pykm}: Total distance driven per year (km/year)
T_{nc} : Total number of vehicles (e.g., cars)
D_{Apy} : Average distance driven per car per year (km/car/year)

Hence, B.A.U method is used as a reference scenario to evaluate the impact of new technologies such as, in the context of biohydrogen in transportation or policies by projecting future emissions without any intervention [37]. This technique holds significance as it enables the precise estimation of future CO_2 emissions from thereby providing valuable insights into long-term environmental trends and facilitating informed decision-making in sustainable development strategies [38]. The Eq. (10) and (11) is used to estimate emissions which serving as a baseline for adaptation of biohydrogen that integrate to project emissions more accurately [39].

$$Q = \sum\nolimits_{i,j} (d_{i,j} \cdot S_{i,j}\ .\ \varepsilon_{i,j} \cdot EF_{i,j} \tag{10}$$

Where:

Q = Total CO_2 emissions (kg or tons).
d_{ij} = Distance traveled (e.g., km) for transportation mode i using fuel type j.

S_{ij} = Number of trips, vehicles, or activity share for mode *i* and fuel *j*.
ε_{ij} = Average fuel economy (L/km or MJ/km) for mode *i* and fuel *j*.
EF_{ij} = CO_2 emission factor for fuel *j* (kg CO_2 per unit of fuel consumed).

$$CE_t = \frac{Q}{1 + e^{-a(t-b)}} \tag{11}$$

CE_t: Dependent variable representing cumulative CO_2 emissions at time *t* (BAU outcome).
Q: Maximum potential CO_2 emissions in the system (upper bound of the curve).
t: Time variable (e.g., year).
a: Model parameter controlling the steepness of the curve.
b: Model parameter shifting the inflection point of the curve.

In this study, CO_2 reduction was estimated by comparing the emissions from biohydrogen use with those from fossil fuels. Due to limited process-specific inventory data across all life cycle stages, a substitution approach was applied, supported by literature-based LCA values from comparable systems. This provides an indicative emissions profile rather than a complete cradle-to-grave assessment. Future work will focus on conducting a full ISO 14067-compliant LCA using primary data to enable direct benchmarking with blue and green hydrogen pathways. Besides, future work possibly will benchmark biohydrogen production from residues against other clean hydrogen pathways (e.g., renewable electrolysis, SMR with CCS) to assess comparative feasibility, costs, and environmental impacts.

3. Results and discussion

3.1. The world CO_2 emission analysis

The purposes of conducting such analyses in this research section to identify emission trends, assess the impact of global and determine major contributors to CO_2 emissions. Besides, it provides insights into high-impact areas of pollution. This helps in shaping policies, supporting climate action goals, and developing strategies for emission reduction and environmental impacts. The Fig. 2a shows over the past 25 years since 2000–2024 CO_2 emission. A steady increase in emissions from transportation between 2000 and 2019, reaching approximately 8.42 BMt. However, a sharp drop to 6.98 BMt is observed in 2020 due to the COVID-19 pandemic, followed by a recovery trend, reaching around 8.47 BMt in 2024. While, Fig. 2b illustrate percentage share of different transportation mode like road, sea and air. The overall passenger or private cars contribute the highest share 41 % of emissions, followed by medium and heavy commercial trucks 22 %, shipping 11 %, aviation accounts for 8 %, while buses, light commercial vehicles, two/three-wheelers, and railways contribute smaller shares 3–7 %.

Fig. 2c shows the annual emissions from forestry and agriculture have increased from 1.6 BMt in 2000 to 3.5 BMt in 2024. While a decline come to 3 BMt in 2020 due to COVID-19 is noted, followed by a continued rise. Whereas pie-chart Fig. 2d shows the total percentage share of emission from different sectors such as open-field burning is the largest contributor 54 %, followed by farming activities 30 % and emissions from farmers' houses 16 %. The increase in CO_2 emissions was mostly attributed to the co-firing and co-gasification of biomass, which often occurs in open field burning and in farmers' homes. Since 2006, CO_2 emissions have increased due to the increase in the utilization of biomass energy sources that emit CO_2. However, estimates indicate that

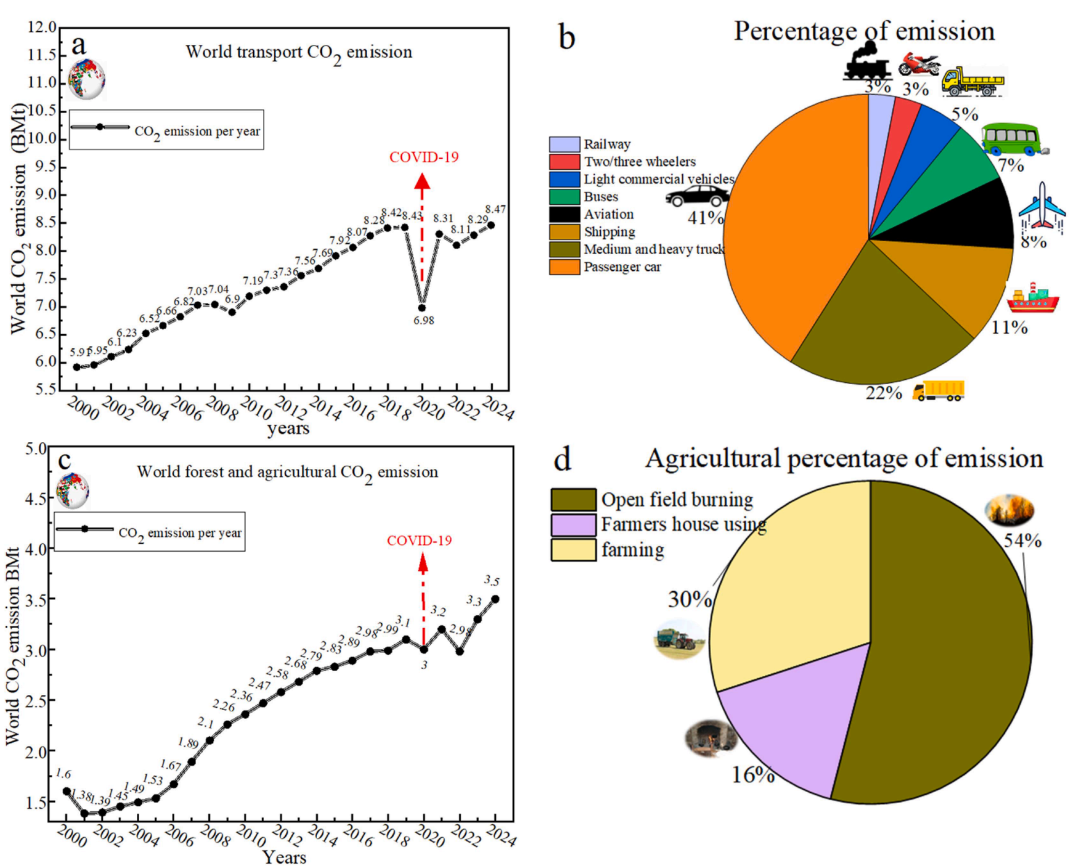

Fig. 2. (a-b) shows the yearly transportation CO_2 emission in BMt and its percentage of from different road, air, and sea, while (c-d) shows the cumulative CO_2 emission in agricultural and forest and its percentage emission from householding, and open filed burning.

net global CO_2 emissions from agriculture, forestry, and other land usage contributed for >8.3 BMt of CO_2 equivalent, or roughly 24 percent of total global GHGs emissions. Overall, the high-impact areas of pollution in transport are passenger cars, heavy trucks, while agricultural emissions are largely due to open-field burning.

3.2. *Prospective analysis of variations in global automotive fuel by 2060*

A prospective analysis offers an in-depth examination of the potential shifts and disparities in the supply of automotive fuels on a worldwide scale over the next four decades. Through comprehensive research and forecasting methodologies, this study endeavors to elucidate the evolving landscape of automotive fuel sources, considering factors such as technological advancements, energy policies, environmental concerns, and market dynamics. By analyzing these anticipated variations, this research aims to provide valuable insights for policymakers, industry stakeholders, and researchers to navigate the future trajectory of automotive fuel provision and its implications for sustainability, energy security, and economic development.

Fig. 3a illustrates the worldwide prediction of the contributions of biofuels, natural gas, and biohydrogen in different sectors such as industry, agricultural, and transportation. The demand of biohydrogen will increase up to 21.5 % in the world by 2060. While graph line of natural gas is going to descending order after 2030 which means countries will more relay on biohydrogen use instead of using natural gas or biofuel (petrol, diesel) due to carbon emission and excessive use of oxygen. After evaluating all characteristics of renewable energy sources, it is expected that between 17–19 % growth will be increased between 2018 and 2028, but the percentage of renewable energy sources will remain relatively small as compare to other energy sources. The production of biofuel is steadily growing and is expected to reach 165 billon litters by the end of the projected period 2028. While biofuels continue to make up over 90 % of the total renewable energy supply in the transportation sector's energy requirement [40].

Moreover, Fig. 3b characterized the demand and role of different types of energy sources such as non-renewable (diesel, petrol), biohydrogen, and other renewable energy sources in transportation sector. Result shows that the trends of CO_2 mitigation are increasing since 2020 by production, demand and consumption of biohydrogen, the expected use percentage of petrol and diesel will be cut from 55–4 %, while the consumption of biohydrogen increases to 93 % by 2060. The roughly number of hydrogen vehicles (HVs) going to increase 0.8 m to 800 m on the road while fuel vehicles decrease 700 m to 0.5 m. As result, CO_2 mitigation emission will lead to the decline from 6.3 BMt to 0.06 BMt by 2060. Besides, Similar to electric vehicles (EVs), hydrogen vehicles (HVs) emit zero harmful emissions from the tailpipe. However, unlike EVs, which require a considerable amount of time to recharge, HVs can be refilled in a timeframe comparable to that of petrol or diesel vehicles. Following extensive testing, researchers affirm that HVs are as safe to drive as gasoline vehicles. Furthermore, in all aspects hydrogen fuel production is comparatively more cost-effective than petrol.

Currently, the transportation sector consumes about 110–115 EJ of final energy annually worldwide. One third of this requirement is fulfilled by fossil fuels and only 3.7 % comes from renewable energy sources [41]. This demonstrates that transportation has the lowest penetration of renewables compared to the other sectors. Global decarbonization scenarios project that the transportation sector will require approximately 125 Mt of hydrogen annually by 2050–60 (≈15–20 EJ), with demand concentrated in hard-to-electrify modes such as long-haul trucking, shipping, and aviation [42].

3.3. *Agricultural and forest biomass residue analysis*

Researchers conduct preliminary assessment of various agricultural and forest residues to determine the quality of available biomass residues for biohydrogen production. Analysis helps to understanding the qualitatively composition and characteristics of crop, livestock, agro-industrial, aquacultural, and forest residues helps in identifying opportunities for their efficient utilization base on availability of feedstocks resources [43]. This could include using them as feedstock for biohydrogen production, composting, or as raw materials for other value-added products. Moreover, by understanding the characteristics and availability of different agricultural and forest residues, researchers can identify techno-economic opportunities for rural communities [44]. This could involve developing small-scale biohydrogen projects, and creating jobs in waste management industries. When land is used for agriculture, a substantial amount of biomass consisting of crop residue is produced each year. However, agricultural biomass residual are distributed resources, each of which varies in terms of its availability across space and time, its geographical location, and the features that it possesses. As shown in Fig. 4 agricultural residues have been divided into four major parts: (i) crop residue, (ii) livestock waste, (iii) Agro-industrial residue, and (iv) aquacultural waste. In this research mainly focused on crop residues.

Forest residue is mainly divided into two parts naming as wood residue and byproduct residue. Woody residue consists of needles, leaves, roots, bark, slabs, edgings, shavings, and sawdust. While the residue that is left behind after cutting down trees, such as chips, slabs, edgings, sawdust, shavings, and hog-ft from the timber market, is considered a byproduct. These biodegradable wastes can be gathered and converted into solid, liquid, or gaseous biofuels that can be burned to generate energy, power, used as an alternative fuel in transportation

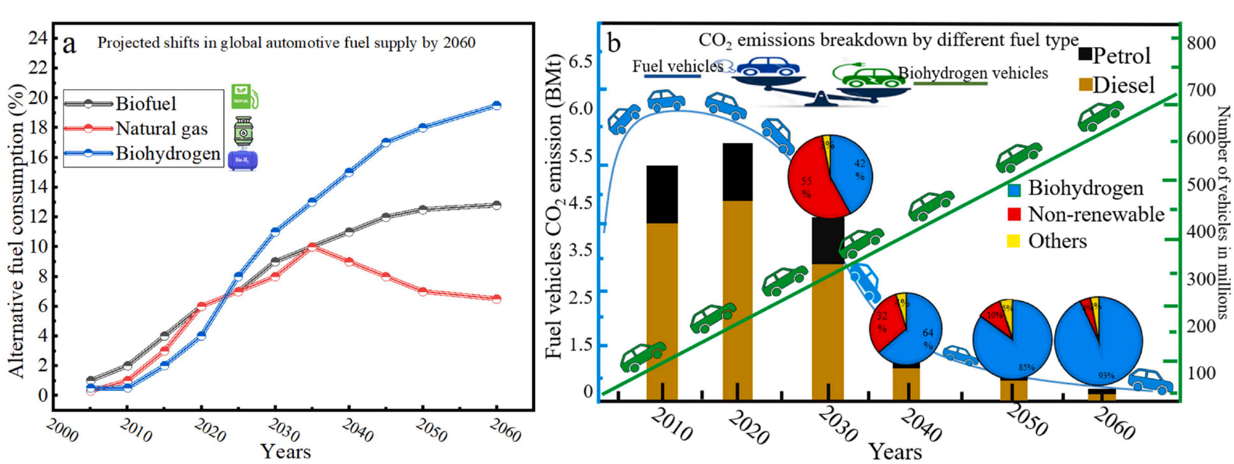

Fig. 3. (a) different automotive fuel: biofuel, natural gas, and hydrogen supply in the world transportation sector by 2060, (b) breakdown of CO_2 emission by fuel types and hydrogen vehicles under B.A.U scenario method.

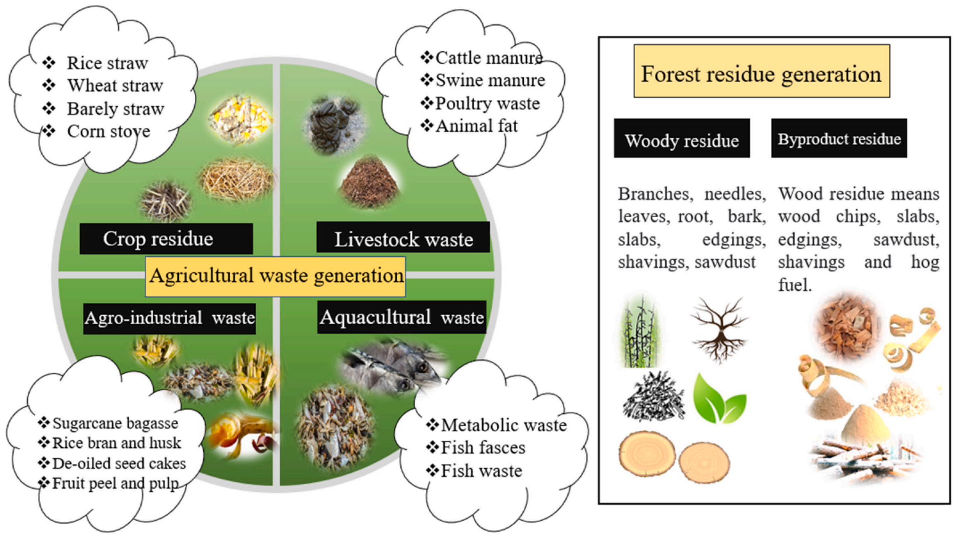

Fig. 4. Crop, livestock, agro-industrial and aquacultural waste are main types of agricultural residues while woody and byproduct waste are forest residue generation.

or industrial applications.

However, utilization rates of agricultural and forestry residues have varied considerably across different periods and regions, reflecting changes in technology, policy, and competing uses [45]. In earlier decades, residues were predominantly used for traditional purposes such as household cooking and heating, whereas in recent years there has been a marked shift toward industrial and modern bioenergy applications, including power generation and biofuel production. At the same time, sustainability requirements such as the need to retain part of the residues to maintain soil fertility and prevent erosion limit the fraction that can be mobilized [46]. Recent assessments by FAO and IEA indicate that while global technical potential remains high, the practically utilized share fluctuates over time and is generally lower than the gross estimates due to collection inefficiencies, economic barriers, and environmental safeguards [47].

3.4. Worldwide agricultural and forest residue generation analysis

Performing a worldwide agricultural and forest residue generation analysis serves several important purposes in the context of research related to biohydrogen production and carbon sequestration in the transport sector fowling: Identifying regions with high agricultural and forest residue generation can aid in selecting suitable feedstock sources for biohydrogen production. This analysis helps prioritize areas where biomass resources are abundant and can be establish the sustainably manufacturing industry, investment opportunities, and technology deployment strategies in the bioenergy sector as well as potential markets opportunity for biohydrogen and related products. Lastly, it's help to international collaboration by collaborative research efforts aimed at analyzing worldwide agricultural and forest residue generation facilitate knowledge exchange and cooperation among researchers, industry stakeholders, and policymakers across different regions. This collaboration can accelerate technological innovation and promote the adoption of sustainable bioenergy solutions on a global scale. That's how this analysis section is very important for this research. China, the U.S.A, Russia, Europe, India, and Brazil are six largest countries that generate the most agricultural and forest biomass residue annually. It is known that forest residues are more as compared to agricultural residues, but the collection, transportation, and management of forest residue pose a great challenge over agricultural residues. Agricultural waste (wheat, maize, rice, soybean, barley, rapeseed, and Sugarcane bagasse) is the best residue for the production of biofuel because easily available for collection from the field [48,49]. These products are generated as a by-product of crop production and their collection and utilization ensure the planned practice and do not affect food scarcity.

Fig. 5a shows the major countries that produce annually agricultural waste residue where China leading with 716 Mt, the U.S.A with 682 Mt, India with 605 Mt, Brazil with 451 Mt, EU with 580 Mt, Pakistan with 285 Mt, Argentina with 148 Mt, and Canada with 105 Mt. China, India, the United States, Europe, and Brazil are the world's largest agricultural producers, in that order, with the biggest residual trash output. Approximately 23Mt of biomass (dry) is available in the EU as leftover straw from cereal crops. The worldwide resource for idle cereal crop waste is now 517 Mt. According to FAO forecast, agricultural land in underdeveloped countries would expand by 13 %, or 120 Mha, between 1999 and 2030. Moreover, agricultural production (producing extra per unit of land) will rise and crop residue productivity in 2050 is expected to be 60 % higher as compare to in 2010–2020. In which the partially met by oil crops in especially cultivation in China and India. As an outcome, worldwide cereal yield is expected to increase and grow up to 3.7 % in coming years.

The other area of interest is forestry, which produces woody biomass waste from both primary and secondary forest sources. The statistics of FAO illustrate those worldwide forest's land cover about 4 Bha (around 32 % of total land area), equivalent to a typical of 0.62 ha/capita. Fig. 5b and Table S1–2 illustrate and summarize the overall global forest residue growing stock per unit area capacity in different continents and countries respectively. The highest production in the tropic's regions is led by South America, Central America and Western and Central Africa (in descending order) respectively [50]. The overall estimated of waste residue which 66.3 % coming from agricultural cereal straw and 33.7 % from timber mills. Instead of burning these wastes in fields, they should be collected, converted into biohydrogen, and used as a fossil fuel replacement to reduce CO_2 emissions.

Table S2 showed the world's leading producers of forest residues, such as; China 517.67 Mt, Russian Federation 168.2 Mt, Indonesia 81.77 Mt, the U.S.A 26.1 Mt, Brazil 133.8 Mt, Sweden 75.58 Mt, France 35.37 Mt, Finland 59.57 Mt, India 62.74 Mt, South Africa 23.74 Mt, Norway 16.72 Mt, and Philippines 12.97 Mt. which generate the annually highest two main primary and secondary forest residues are following: (i) primary source residues: stumps, branches, and leaves, etc., and (ii) Secondary sources timber processing waste such as woody chips, slabs, edgings, shaving, and harvested logs and sawdust. To clarify, major assessments (e.g., FAO statistics and IPCC AR6 scenarios) typically

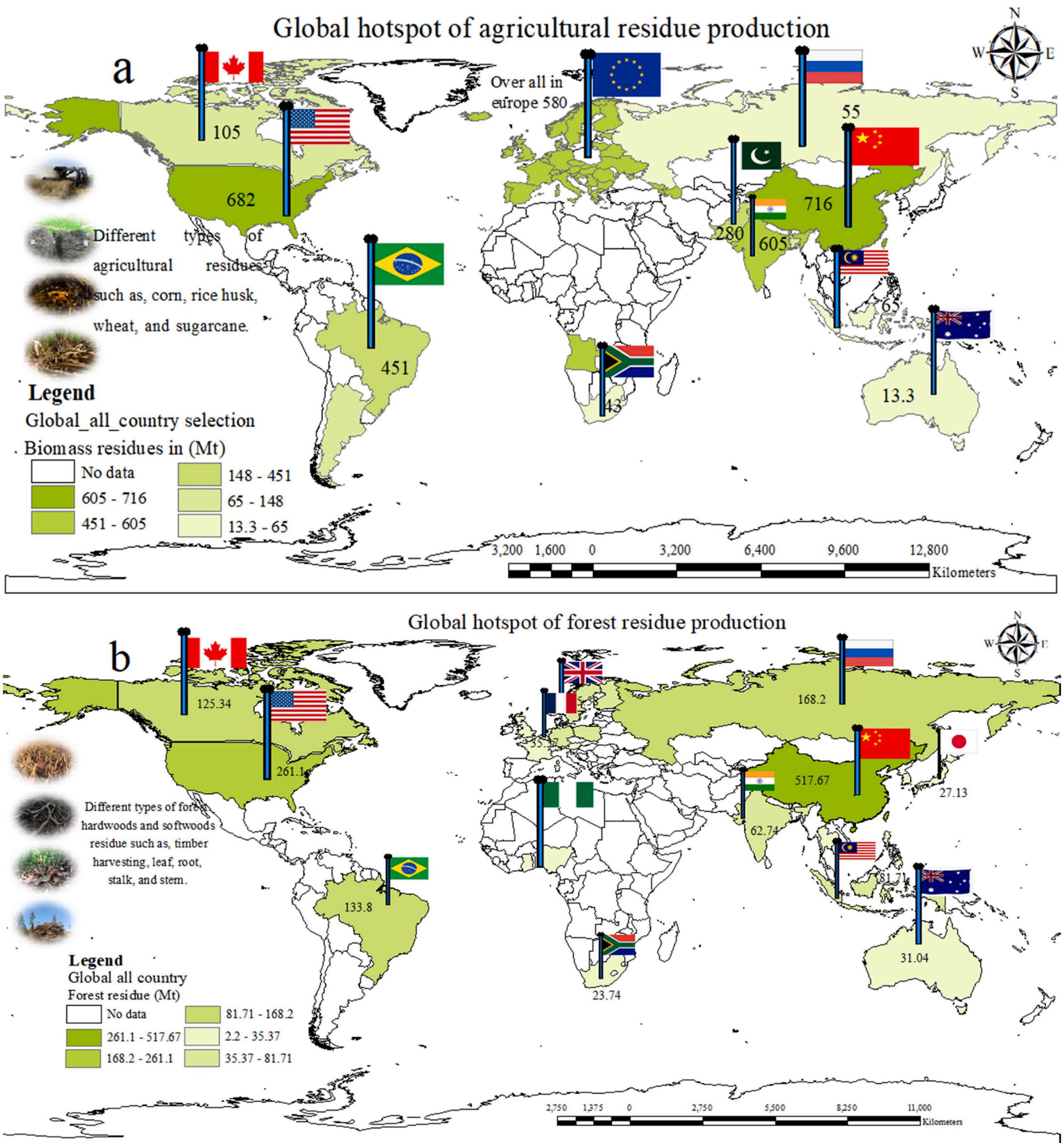

Fig. 5. (a) depicted the annual generation potential of agricultural waste residues in top countries, (b) depicted the global forest residue production. The color dark green to light green illustrate the highest to lowest generation rate of residues.

indicate a technically and economically available biomass residue potential in the range of 5–15 Gt/year globally, which aligns with approximately 40–60 EJ/year of bioenergy potential.

Interestingly, the production of forest biomass residue and its subsequent recovery are both affected by variables such as the type of trees, climatic and geographical circumstances of the area. Moreover, >65 countries submitted the same stock that they reported to FRA 2005 based on the default variables in the IPCC 2003 Good Practice Guidance document (IPCC, 2003). Moreover, it is estimated that forests store 662 Gt (163 tonnes per hectare) of carbon, with 300 Gt in soil organic matter, 295 Gt in live biomass, and 68.0 Gt in dead wood and litter. Soil organic matter holds 45.2 % of all carbon above- and below-ground biomass, litter, and dead wood follow.

3.5. Prospective waste residue collection and management challenges

The generation and recovery of waste residues depend on several factors, including tree species and local geographical conditions. Fig. 6 presents an overview of the collection-to-transportation chain for forest residues destined for biohydrogen production. Three primary methods are commonly applied: (i) bundling, (ii) roadside chipping, and (iii) terrain chipping. These methods facilitate efficient collection and transportation of residues for energy applications [51]. In addition to field residues, secondary woody wastes are produced during timber processing. These include bark, sawdust, wood chips, slabs, edgings, shavings, hog fuel, and black liquor. Such residues are typically low in moisture, uniform in quality, and readily available on-site. While they can be directly used for heating, cooking, electricity generation, and production of bioproducts such as charcoal and pellets, uncontrolled direct use often results in GHG emissions and environmental pollution. A

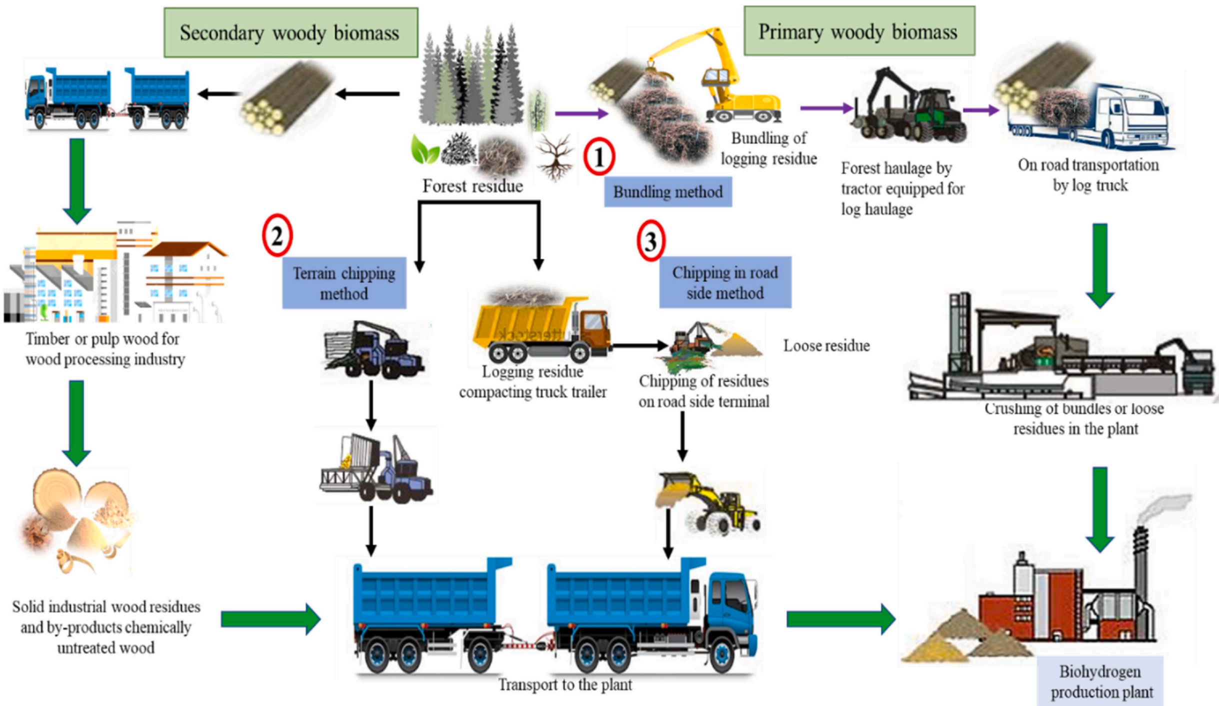

Fig. 6. Flowchart of forest primary and secondary woody biomass collection, processing, and transportation pathways for biohydrogen production.

more sustainable pathway is to channel these residues into clean energy plants for the production of biohydrogen, bioethanol, and other renewable fuels. According to estimates by the USDA Forest Service, approximately 83.4 Mt of timber and bark processing wastes were generated in 2020, with nearly 98 % collected, burned, or otherwise rendered unusable.

Despite these opportunities, several challenges remain across the harvesting, collection, transportation, management, and utilization stages [52]. Addressing these barriers requires coordinated policy frameworks, effective implementation, government and organizational support, and active participation of stakeholders. Measures such as satellite monitoring, stricter enforcement of laws restricting open burning, public–private partnerships, and farmer training can play critical roles [53]. Awareness campaigns through mass and print media can also promote residue collection while discouraging environmentally harmful practices.

Notably, utilizing agricultural and forestry residues for biohydrogen can reduce fossil fuel dependence and CO_2 emissions, potential environmental trade-offs should be considered. While residue extraction for biohydrogen production must be balanced with the need to maintain long-term soil fertility. Crop residues play a critical role in sustaining soil organic matter, nutrient recycling, and erosion control, especially in regions with marginal productivity. Complete removal is therefore neither feasible nor desirable. Sustainable management practices suggest that only a fraction of residues (typically 30–50 %, depending on crop type, soil conditions, and climate) can be removed without adversely affecting soil health. In practice, this means that the actual biohydrogen potential will be lower than the gross technical estimates presented in this study. Complementary measures, such as returning biochar, compost, or other organic amendments, can further help to mitigate nutrient depletion and maintain soil productivity over the long term.

3.6. Biohydrogen production analysis

Analyzing the collection of agricultural and forest residues for the production of biohydrogen and its utilization in various sectors as a green technology provides insights into developing sustainable energy solutions that address waste utilization, green technology for renewable energy source, environmental benefits, economic opportunities, and social challenges. Moreover, agricultural and forest residues often pose disposal challenges and can contribute to environmental issues such as pollution and GHGs if left unmanaged. By utilizing these residues for biohydrogen production, holders can effectively convert waste into a valuable energy resource, reducing environmental impacts as well as great economic opportunity for farmers and forest owners through the sale of residue for energy production. Lastly, biohydrogen can be generated through biological processes such as fermentation or gasification of biomass than other traditional technologies due to low carbon footprint, and compatibility of existing infrastructure.

Dark-photo fermentation is frequently cited as a promising route for biohydrogen due to its ability to utilize wet biomass under mild conditions. However, practical scalability remains limited by low hydrogen yields, long retention times, nutrient requirements, and sensitivity to operational parameters. In contrast, thermochemical routes such as gasification and pyrolysis have reached larger pilot and demonstration scales, offering higher energy efficiency and integration potential for industrial applications. Hybrid approaches, combining dark-photo fermentation with thermochemical upgrading, are being explored to improve yield and scalability. Pilot-scale studies of dark-photo fermentation, for instance, demonstrate feasibility on small waste streams, while gasification-based systems have been implemented at regional demonstration plants [54]. Overall, Dark-photo fermentation may be suitable for decentralized, low-cost waste-to-hydrogen applications as well as high content of left over waste residue after biohydrogen production which can be used for maintain the soil fertility [55]. Whereas thermochemical and hybrid pathways provide more scalable solutions for industrial-scale hydrogen production [56–58]. Table S3 provides a comparative overview of these routes, highlighting differences in scalability, hydrogen yield, efficiency, technical complexity, and demonstration status, and illustrating the trade-offs between decentralized and industrial-scale deployment.

Fig. 7 represents a schematic for bio-hydrogen production from cellulose and starch-containing waste residues by collecting two stages

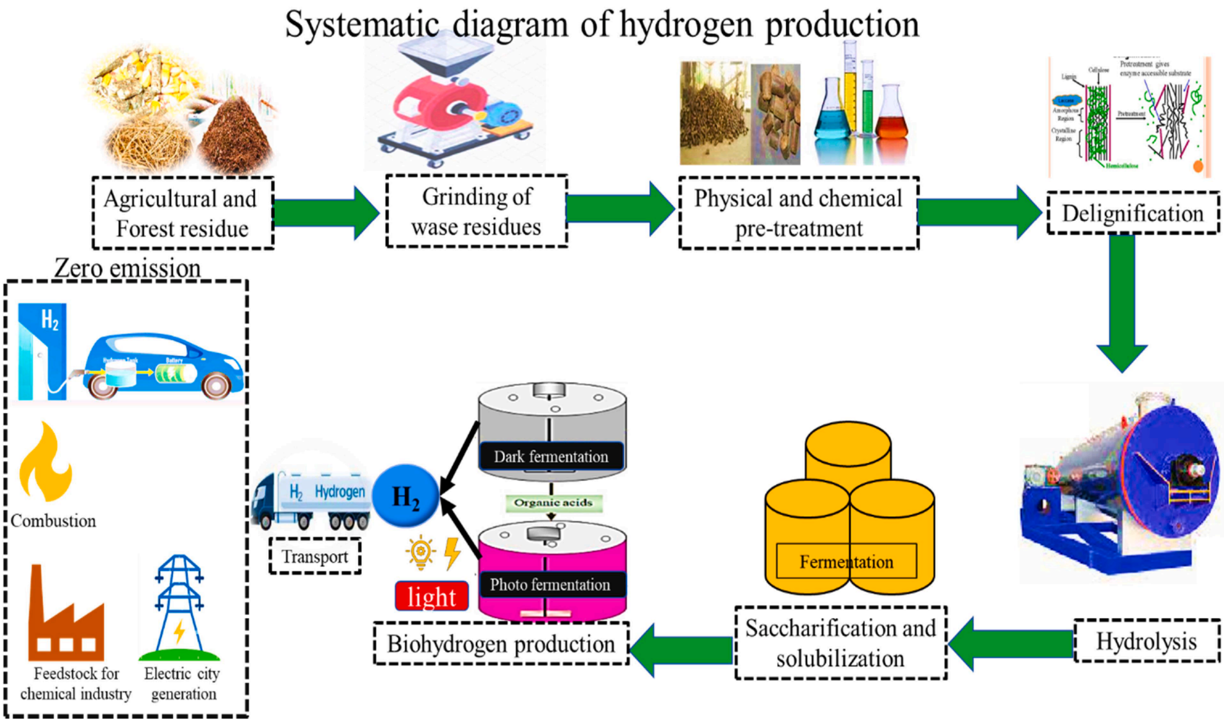

Fig. 7. The collection of agricultural and forest residues for production of biohydrogen and utilization in different sectors as a green technology.

anaerobic dark and photo-fermentations. Interestingly, biomass fermentation processes such as anaerobic digestion generate residual solids (e.g., digestate, lignocellulosic residues). These residues can be effectively utilized rather than discarded, thereby enhancing the overall resource efficiency of the biomass utilization chain. For example, digestate can be applied as an organic fertilizer or soil conditioner due to its high nutrient content (N, P, K), reducing reliance on synthetic fertilizers and avoiding the associated CO_2 emissions from their production [59]. Lignocellulosic residues can be further processed for biochar production, which can be applied to soils for long-term carbon sequestration [60]. Additionally, coordinated strategies to reduce CO_2 emissions involve integrating fermentation within circular bioeconomy frameworks such as coupling with renewable energy systems [61], optimizing transportation logistics to minimize fossil fuel use, and applying life-cycle assessment to identify emission hotspots thereby ensuring that both energy recovery and residue valorization contribute to net GHG reduction [62].

The use of biohydrogen in the transportation, electricity generation, industrial and combustion sector as a green technology. The following procedure for collection to production and utilization of biohydrogen are summarized as well. On the other side, for large-scale commercialization of biohydrogen production has two major challenges low yield and high production cost. Due to the complicated nature of biomass waste which is composed of cellulose, hemicellulose and lignin, which may unfavorably consequence on production processes that's why requires further pre-treatment before production of hydrogen processes. Thus, collected agricultural and forest waste residues is sent to the grinding section which can be processed either by mechanical or chemical processes. It has been found that there is an inverse link between the amount of lignin present in agricultural wastes and the effectiveness of enzymatic hydrolysis of such wastes [63].

The sensitivity analysis indicates in Supplementary Fig. S1 (a-b) and Table S4–5 that collection efficiency and residue-to-product ratios are the most influential parameters, with up to ±30 % variation in total hydrogen potential. In contrast, transport/logistics losses show relatively minor effects. This highlights the importance of improving residue collection systems and yield optimization for realistic deployment scenarios. Moreover, based on major assessments, 5–10 Gt of biomass residues are technically and economically available each year. Assuming hydrogen yields of 20–80 kg/t, this corresponds to a gross potential of 0.1–0.8 Gt H_2 (12–96 EJ). Applying sustainability constraints (10–30 % recoverability), the usable potential narrows to ≈0.01–0.24 Gt H_2 (1–29 EJ). This demonstrates that while biomass residues can make a valuable contribution to hydrogen supply, realistic potentials are an order of magnitude smaller than gross theoretical estimates based on inflated residue statistics (e.g., 140 Gt), underscoring the need for sensitivity analysis and region-specific evaluations. Lastly, Fig. S1-c, blue line represents the mean forecast. While, the shaded area shows the 5th-95th percentile range, reflecting uncertainty from variations in crop yield, land availability, and conversion efficiency. we can see how the uncertainty grows slightly over time due to the cumulative effect of parameter variability.

3.6.1. Estimating biohydrogen production capacity by agricultural residues

The continent analyses in research facilitate detailed understanding the regional variation, resource assessment, data availability, global perspectives, resource distribution, waste valorization, comparative analysis, and sustainability, which helps to making policies and targeted interventions to address diverse challenges, opportunities across different regions of the world. Conducting an analysis helps in assessing the available biomass resources and estimating the potential biohydrogen production capacity from these sources. Several regions of the world like South Asia, East Asia, North America, and Europe are abundant in agricultural waste residues due to factors such as large-scale agriculture, crop diversity, Industrial processing, and climate conditions. Subsequent these regions are abundant in agricultural waste residues, providing ample opportunities for the utilization of waste biomass for various purposes, including animal feed, soil amendments, and bioenergy production. The total production of biohydrogen is around 65 Mt on an annual basis in which 48 % of the total amount is derived from natural gas, 30 % from chemicals [64], 18 % from coal, and 4 % from electrolysis), and it is expected that this number would rise to approximately 150 Mt by the year 2040 to 2060 [65]. As a result, the agricultural residue depicted in Fig. 4 has the potential to contribute around

16–18 % of the world's need for hydrogen. Various parameters have been used to estimate collectible agricultural residue, and the production capacity of biohydrogen. The highest production of agricultural residue is from sugarcane which is about 10.7 kg H_2/t and RPR capacity bout 8.06 t, secondly corn, is 9.11 kg H_2/t and production are 1 kg H_2/t, thirdly Oats 8.98 kg H_2/t and production ratio is 1.3/t. While sugar beet has lowest 6.22 kg H_2/t and the production ratio is 0.7/t of biohydrogen as compared to other agricultural residues, summarized in Table S6.

Fig. 8 shows the biohydrogen production results from agricultural residues (potato, wheat, corn, sugarcane, rice, sugar beet, and barely) in different continents of the world: Asia Europe, North America, Central America, South America, Africa, and Oceania by 2020 to 2040. In last two decay 2020, and 2030, Fig. 8a shows Asia has the highest production of crops residue and as results higher production of biohydrogen capacity. Mainly the rice husk (1150 kt-1650 Kt), sugarcane bagasse (1000 kt-1510 Kt), corn straw (450 kt-520 Kt), wheat straw (400 kt-500 Kt) can be used for generation of biohydrogen. It is predicted that in coming decay 2040, the increase of 70 % to 80 % in crops residue is expected. Secondly, Fig. 8b in Europe almost all kind of mentioned agricultural waste residues has been used for production of biohydrogen, and it is predicted that increase in hydrogen production by wheat (410 kt-520 kt), corn (190 kt-240 kt), sugar beet (180 kt-230 kt), and Potato (150 kt-160 kt) up to 20 % to 25 % by 2030 to 2040 respectively. Thirdly, Fig. 8c North America, corn, sugar beet, and wheat straw has been using for production of hydrogen. The production of biohydrogen will be increased during period of 2030–2040 corn (500.6 kt-1050 kt), wheat (100 kt-140 kt), sugarcane (10 kt-20 kt).

Fig. 8d and 8e central America and south America show only sugarcane and corn has been using for production of biohydrogen while in south America the rice husk is using as pilot scale. Moreover, the production and collection of sugarcane residue is higher in south America than other continents of the world. As a result, the higher production of biohydrogen will be by sugarcane residue in coming decade. On the other side the production by sugar beet residue was in 203 kt will going to decrease and come to 30.2 kt. it may be the effect cultivation of this crop in this region. In Africa Fig. 8f potato, wheat, corn and rice is used for production of hydrogen and it is predicted that in coming decade by 2040 the overall production ratio will be less than previous decade it might be due to less cultivation or drought etc. Lastly Oceania Fig. 8g showing the only two types of residue sugarcane and rice for production of biohydrogen which is least generation in this region than another continent of the world.

Across regions, biohydrogen production potential by different biomass residue displays strong spatial heterogeneity, with Asia and South America emerging as the dominant contributors. Asia shows the fastest growth, rising from ~1150 kt in 2020 to over 2280 kt in 2040, largely driven by rice and sugarcane residues, while South America follows with ~1160 kt to ~2900 kt, overwhelmingly dependent on sugarcane. North America and Europe contribute moderately, with increases from ~500 to 1050 kt and ~130 to 520 kt, respectively, primarily from corn, wheat, and barley residues. In contrast, Central America, Africa, and Oceania remain minor contributors, each below 150 kt by 2040, with sugarcane and corn residues dominating in the tropics and cereals in temperate zones. Overall, these results emphasize that global biohydrogen supply is both regionally concentrated and feedstock-specific, with >70 % of the potential concentrated in Asia and South America by 2040.

3.6.2. Estimating biohydrogen production capacity from forest residues

Several regions of the world are abundant in forest waste residues due to factors such as forest cover, forestry practices, and timber processing activities. Some of the regions that are particularly abundant in forest waste residues include North America, Asia and Northern Europe. These regions can provide opportunities for sustainable utilization and valorization of biomass for purposes such as wood products manufacturing, ecological restoration, and bioenergy production. However, biohydrogen production from forest residues faces a number of challenges. Biomass collection and pre-treatment are the most important problem to be overcome for production of biohydrogen. Currently some continents of the world are trying to make good management policies for achieving the high quality and quantity of biohydrogen for fulfil the energy demand. In Fig. 9 shows Asia, Europe, and North and Central American regions are taking good initiatives for production of biohydrogen by forest primary and secondary waste residues.

Both primary and secondary forest residues can be utilized for the production of biohydrogen, but the availability and suitability may vary depending on factors such as location, forest management practices, and processing techniques. Fig. 9a illustrate the production of biohydrogen through secondary residue was 67Kt in 2020 which could be increased 98–105Kt by 2030–40 providing adaptation of best practices by different countries of this region like Russia, Indonesia, Malaysia, and Thailand as one of the world's largest forested countries, Russia possesses immense forest resources spanning across its vast landmass. Logging operations, as well as natural disturbances like wildfires and insect infestations, contribute to the generation of forest residues in Russia, including branches, tops, and woody debris.

Fig. 9b showed the primary biohydrogen production yield is higher than another continent of the world. The reason is that Scandinavian countries like Norway, Sweden, and Finland have abundant forest resources due to their extensive coniferous forests. Moreover, these countries have advance technologies for best practice collection, management and using these primary sources for production of energy sources. Moreover, as secondary residue generation Northern European countries such as Sweden, Finland, and Russia, are characterized by vast forested landscapes, including boreal forests and taiga ecosystems. Timber production, pulp and paper manufacturing, and sustainable forestry practices result in significant amounts of secondary forest residues such as bark, sawdust, and wood chips. Secondary forest residues are often considered suitable feedstocks for biohydrogen production due to their uniform size, high lignocellulosic content, and consistent quality. They are typically easier to collect, handle, and process compared to primary forest residues. The comparatively other continent of the world in America has highest yield and production of biohydrogen through forest residue. While in comparative to Fig 9c. North America was highest production through primary residue as compare to Central America Fig. 9d and South America Fig.9e. In North America Both the United States and Canada have extensive forested areas, including boreal forests in Canada and temperate forests in the United States. Timber harvesting, forest management practices, and natural disturbances could be increasing the production of bio-energy.

In Fig. 9f African continents had lowest production of biohydrogen as compare to other continent of the world through primary and secondar forest due to the Limited Infrastructure and Technology, extensive traditional biomass use, lake of management policies, and production technologies. The utilization of forest residues for the production of biohydrogen in Africa faces both opportunities and challenges compared to other continents of the world. The percentage yield can be increased through policy and regulatory frameworks, management practices and technologies can be sued in vast forested countries due to diverse ecosystems, such as the Democratic Republic of Congo, Gabon, and Cameroon where possess extensive forest resources. These forests potentially can offer abundant sources of forest residues for biohydrogen production. In Fig. 9g Oceania some time referred to Australia showed least amount of production as compare to other continents of the world. The main reason is Oceania, consisting of numerous islands and countries scattered across the Pacific Ocean, does face challenges in research and resources for forest biomass residue utilization for biohydrogen production.

Across regions, biohydrogen production shows a consistent dominance of secondary residues over primary residues, underscoring their greater contribution to future hydrogen supply. Asia leads with

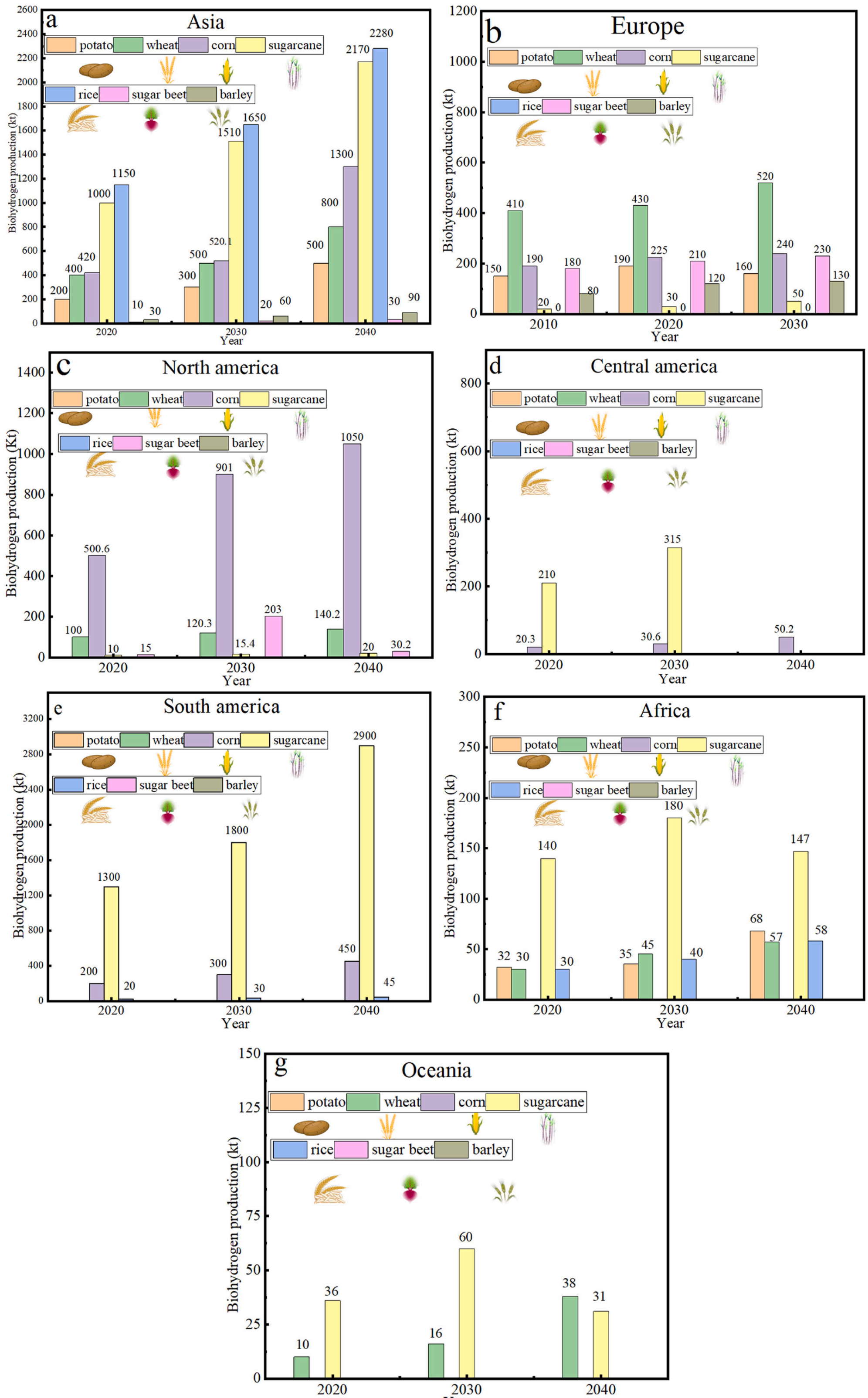

Fig. 8. Show the production of biohydrogen by different crop residue potato, wheat, corn, sugarcane, rice, sugar beet, and barley. In different region of the world: North America, Europe, Asia, central America, south America, Africa, and Oceania.

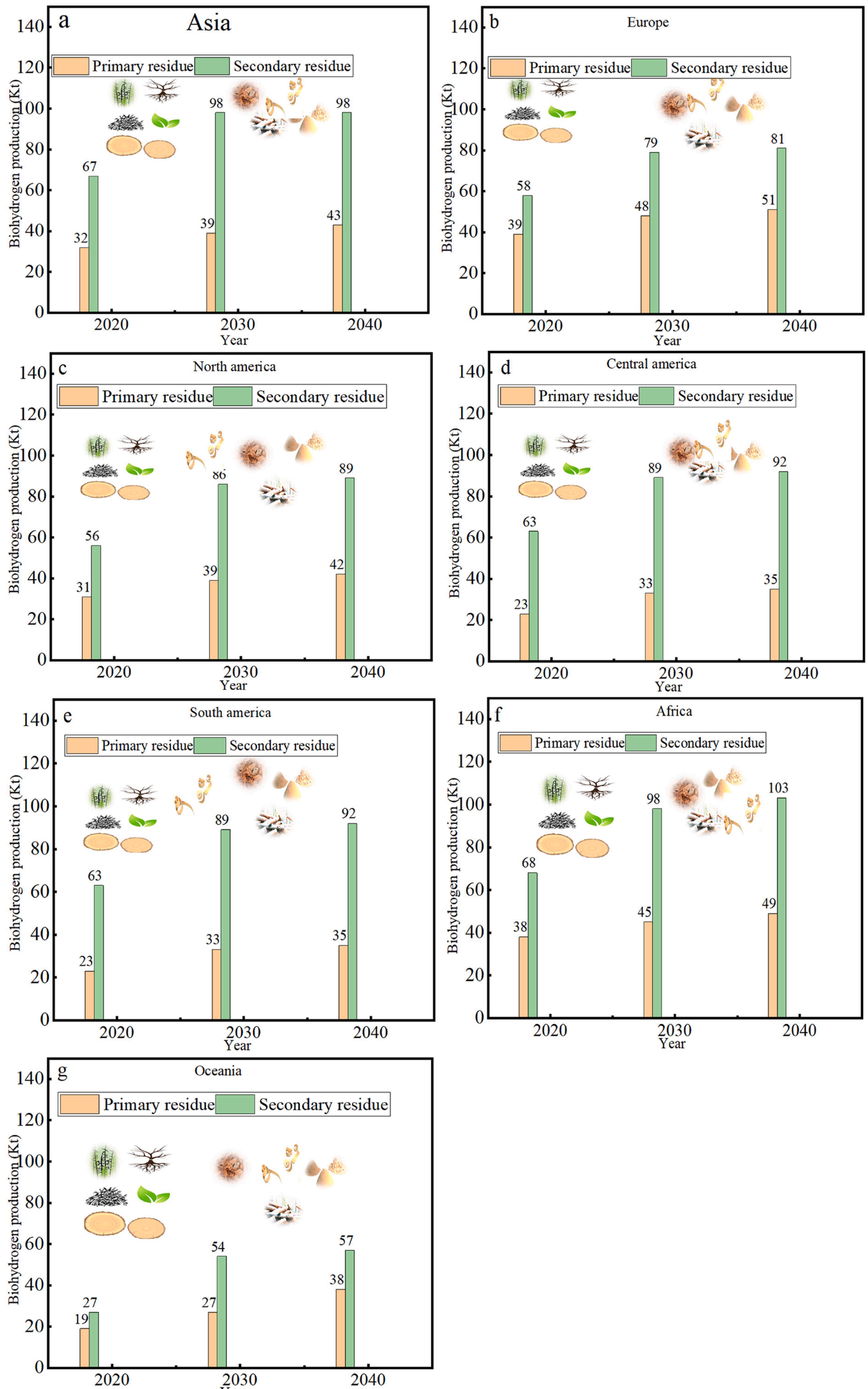

Fig. 9. Show the production of biohydrogen by different forest primary and secondary residues, In different regions of the world: North America, Europe, Asia, central America, south America, Africa, and Oceania.

secondary residues contributing nearly ~98–100 Kt throughout the projection period, followed by Europe, North America, and South America, each maintaining ~80–90 Kt by 2040. In Africa, secondary residues also rise steadily (68–103 Kt), while primary residues remain below 50 Kt. Central America and Oceania exhibit comparatively smaller but stable contributions, with secondary residues (~90 Kt and ~57 Kt, respectively) exceeding primary residues by wide margins. Overall, these results emphasize that while regional scales differ, secondary residues consistently represent the backbone of global biohydrogen potential, highlighting the strategic importance of improving collection and utilization systems for these feedstocks.

3.7. CO_2 emission reduction by agricultural residues

Crop residue collection shows in Fig. 10a steady growth over time. Corn, rice, and sugarcane dominate globally, with wheat residues rising from 260 Mt (2020) to 360 Mt (2040). sugarcane follow closely (280–410 Mt), while rice remains consistently high (190–280 Mt). Other crops (corn, barley, sugar beet, potato) contribute relatively smaller shares, each below 200 Mt by 2040. While biohydrogen production potential reflects the same hierarchy as crop residues in Fig. 10b wheat residues yield the highest production, rising from 2600 Kt in 2020 to 3860 Kt in 2040. Rice and sugarcane residues also make significant contributions, exceeding 2000 Kt by 2040. Corn and barley provide moderate contributions (~1800–2100 kt), while potato and sugar beet contribute the least (<1200 Kt). This indicates that wheat, rice, and sugarcane residues are the backbone of global biohydrogen supply. Overall, results show that 1840 Mt agricultural waste residues could be collected and produce 15,460 kt of biohydrogen by 2040.

While overall CO_2 emission reduction by agricultural crops residue has shown in Fig. 10c, a total CO_2 emission reduction 75.5 Mt by 2020, Fig. 10d, 82.09 Mt CO_2 emission reduction by 2030, and Fig. 10e 86.15 Mt CO_2 emission reduction by 2040 which is continuously going to ascending order. Across the projection period, CO_2 emission reductions are consistently dominated by sugarcane residues, which contribute ~29.28 Mt CO_2 eq in 2020 and rise to ~31.28 Mt CO_2 eq by 2040. Corn remains the second-largest contributor (~14.74 Mt CO_2 eq), followed by rice (~13.57 Mt) and wheat (~9.18 Mt), all of which show gradual increases over time, while potato, barley, and sugar beet residues provide only marginal reductions (<5 Mt CO_2 eq). These findings highlight that the global mitigation potential is heavily concentrated in sugarcane, rice, wheat and major cereals, making them strategic feedstocks for biohydrogen production. Harnessing these residues not only avoids open-field burning and waste accumulation but also provides a dual benefit of renewable energy generation and substantial GHGs mitigation, positioning biohydrogen as a critical pathway for sustainable decarbonization.

To sum up, the percentage of collection and production of biohydrogen in Mt by wheat, sugarcane and corn residues are higher than potato, sugar beet, barley, and rice residues. The overall collection, and production of hydrogen, and CO_2 emission reduction is higher than forest residues. As a result, agricultural leftovers residues are excellent materials for the production of biohydrogen which may be utilized as an additional source to reduce CO_2 emissions and societal costs, save natural gas, and supply agricultural crops with the nitrogen they require.

3.8. CO_2 emission reduction by forest residues

The results provide a comprehensive assessment of global forest residue availability, its potential for biohydrogen production, and the corresponding CO_2 emission reduction benefits. Fig. 11(a-b) demonstrate a steady increase in both primary and secondary forest residues from 2020 to 2040. Secondary residues dominate throughout the period, rising from 410 Mt in 2020 to 614 Mt in 2040, whereas primary residues increase more moderately from 217 Mt to 315 Mt. This disparity reflects the relative ease of collecting secondary residues from timber and wood-processing industries, compared to the more distributed and logistically challenging primary residues such as branches, leaves, and tops.

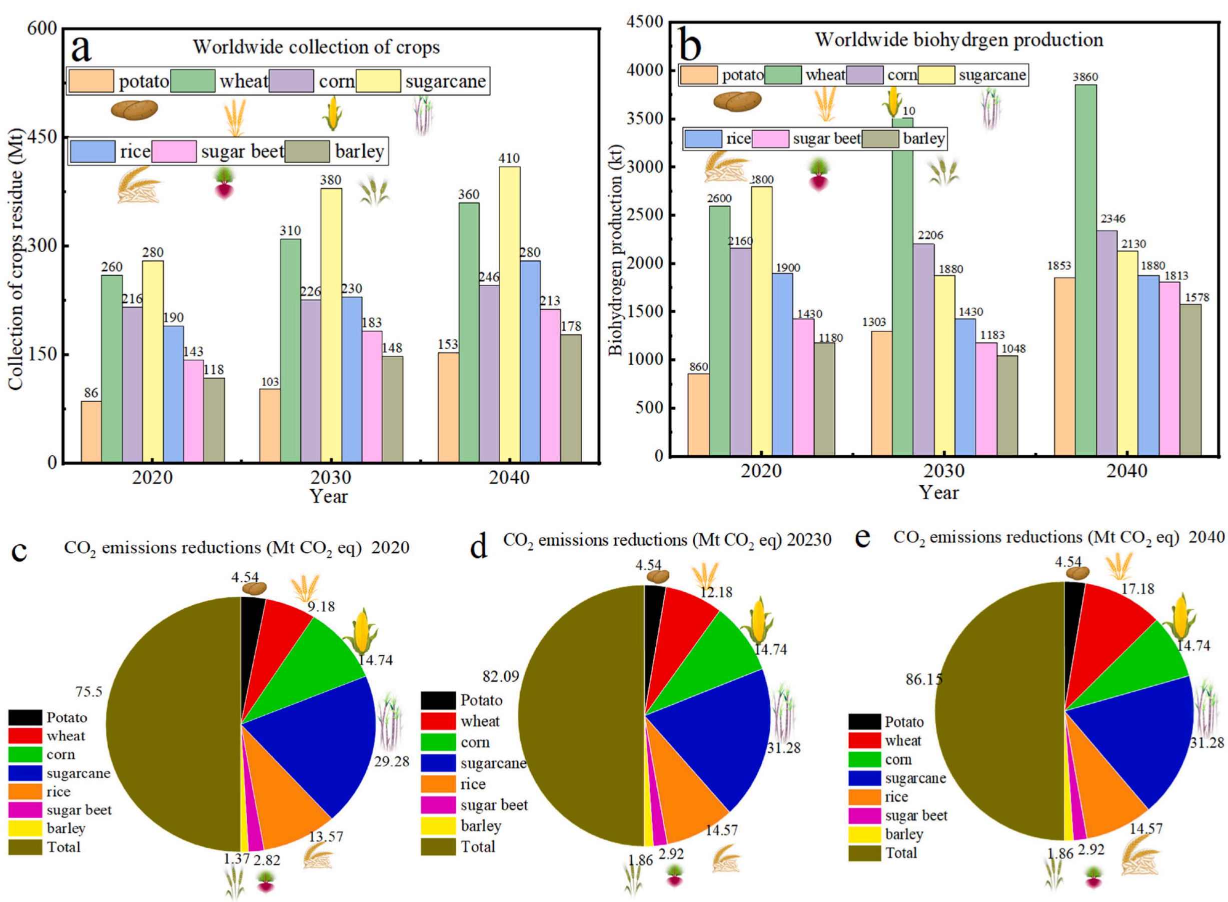

Fig. 10. a collection of agricultural potato, wheat, corn, sugarcane, rice, sugar beet and barley waste residues, b biohydrogen production capacity by 2020 to 2040, while the Pie chart (c), (d), and (e) Illustrate the CO_2 emission reduction by 2020 to 2040.

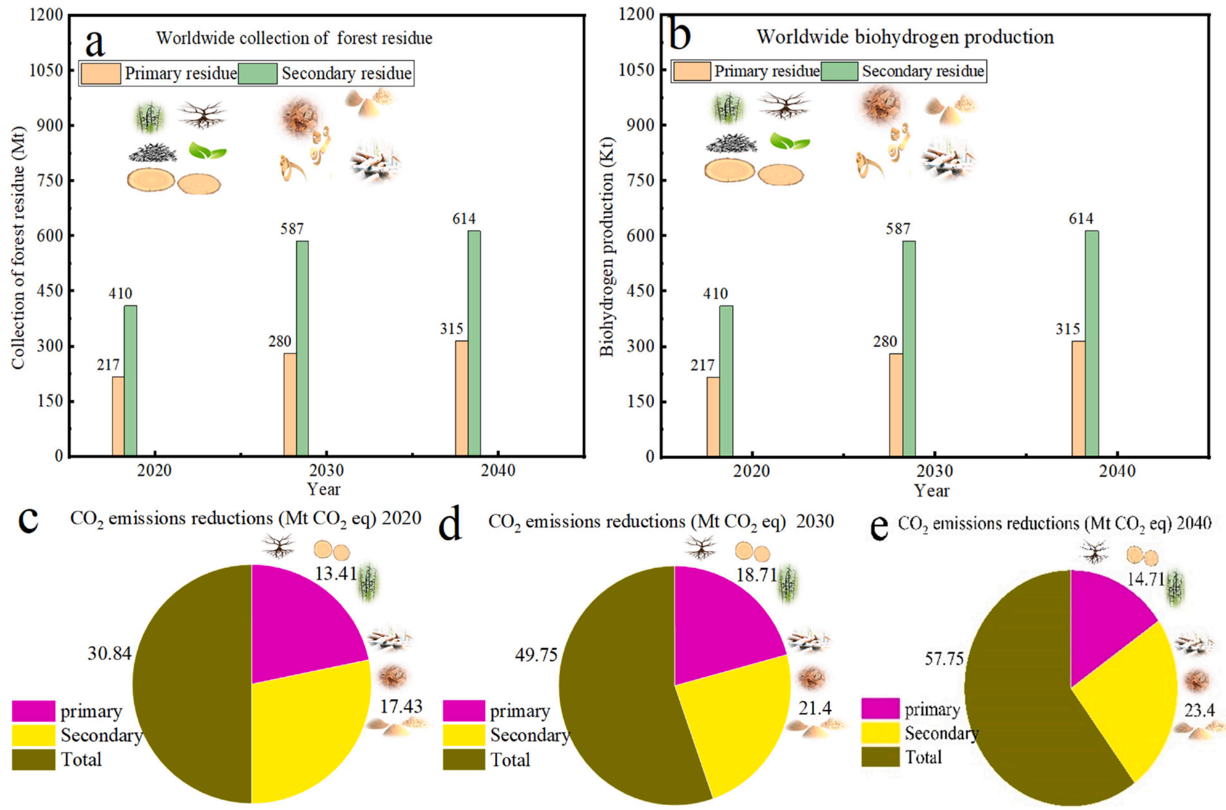

Fig. 11. a show the collection of primary and secondary forest residue, (b) biohydrogen production capacity, while the Pie chart (c), (d), and e Illustrate the CO_2 emission reduction by 2020 to 2040.

Biohydrogen production potential closely mirrors residue availability, with secondary residues providing almost twice the yield of primary residues across all years. By 2040, secondary residues alone could generate 614 Kt of biohydrogen compared with 315 Kt from primary residues. Fig. 11(c-e) further highlight the CO_2 emission reduction potential of substituting fossil fuels with biohydrogen derived from forest residues. Total reductions increase from 30.84 Mt CO_2 eq in 2020 to 57.75 Mt CO_2 eq in 2040, with secondary residues contributing the larger share (23.4 Mt CO_2 eq in 2040). Primary residues peak in 2030 at 18.71 Mt CO_2 eq reductions but decline slightly by 2040, indicating possible collection constraints or efficiency limits in their utilization.

These results underscore the strategic importance of secondary residues as a reliable and scalable biomass stream for biohydrogen pathways, while also highlighting the need for improved management, monitoring, and supportive policies to unlock the underutilized potential of primary residues. It is further noted that the hydrogen yield and quality from forest residues are generally lower than from agricultural residues, owing to differences in species composition and structural characteristics. Nonetheless, the integration of both residue streams into future biohydrogen supply chains could deliver meaningful contributions to clean energy transition and climate mitigation.

3.9. *Forecast of mitigation of CO_2 emission from 2010 to 2060*

Predict future trends analysis where researcher seek to anticipate the trajectory of emissions reduction over the coming decades. Research analysis contributes the broader objective of achieving sustainable development goals by providing valuable information on the progress towards reducing CO_2 emissions. This allows the researchers and experts to understand the potential effectiveness of current mitigation efforts and identify areas for further improvement. Moreover, help evaluate the effectiveness of adopted mitigation strategies, allows decision-makers, stakeholders, and the public to assess the long-term environmental, social, and economic impacts such as climate change mitigation, air quality improvement, public health, and sustainable development. Moreover, information can guide the development and implementation of more effective policies and strategies to accelerate mitigation efforts [66]. The bottom-up accounting model with a business-as-usual scenario was considered for a globally distinct assessment of mitigation of CO_2 emissions from the past to the present, and the future emission trend was anticipated using this framework. Fig. 12 characterizes the geographical explanation from 2010 to 2060 of per capita CO_2 emissions reduction by adopting strategies i.e., stop open field burning and production of biohydrogen from agricultural, forest residues and use this biohydrogen as a clean fuel in agricultural and transportation sectors.

It is evident by looking at the statistic that developed or advanced countries like North America, France, the U.K, Sweden, Germany, Poland, Norway, Spain, and Italy have higher per capita CO_2 emissions as compared to the rest of the world which is due to the open field burning of wastes and transportation emission. Moreover, because to the robust economic circumstances in western European countries such as Denmark, the United Kingdom, Ireland, and France, would have a higher emission rate as compare to central and eastern European countries in 2010, 2020, and 2030 respectively. In addition, it can be noted that China has developed as one of the utmost countries in Asia to emit high CO_2 emissions in all aspects in the year 2020. This is owing to the country's rapid economic expansion as well as its massive production in the agricultural and transportation sectors. However, the overall emission rate in Asia and Africa is relatively low since many of the countries in those regions are still growing.

In the year 2020, the United States is responsible for the largest and most significant quantity of CO_2 emissions that are released into the atmosphere worldwide. The agricultural and forest open field burning in the United States contributed 1.32 BMt CO_2 to the atmosphere, while the transportation sector was responsible for 1.63 BMt CO_2 emissions. whereas China was the second greatest donor, with agriculture and

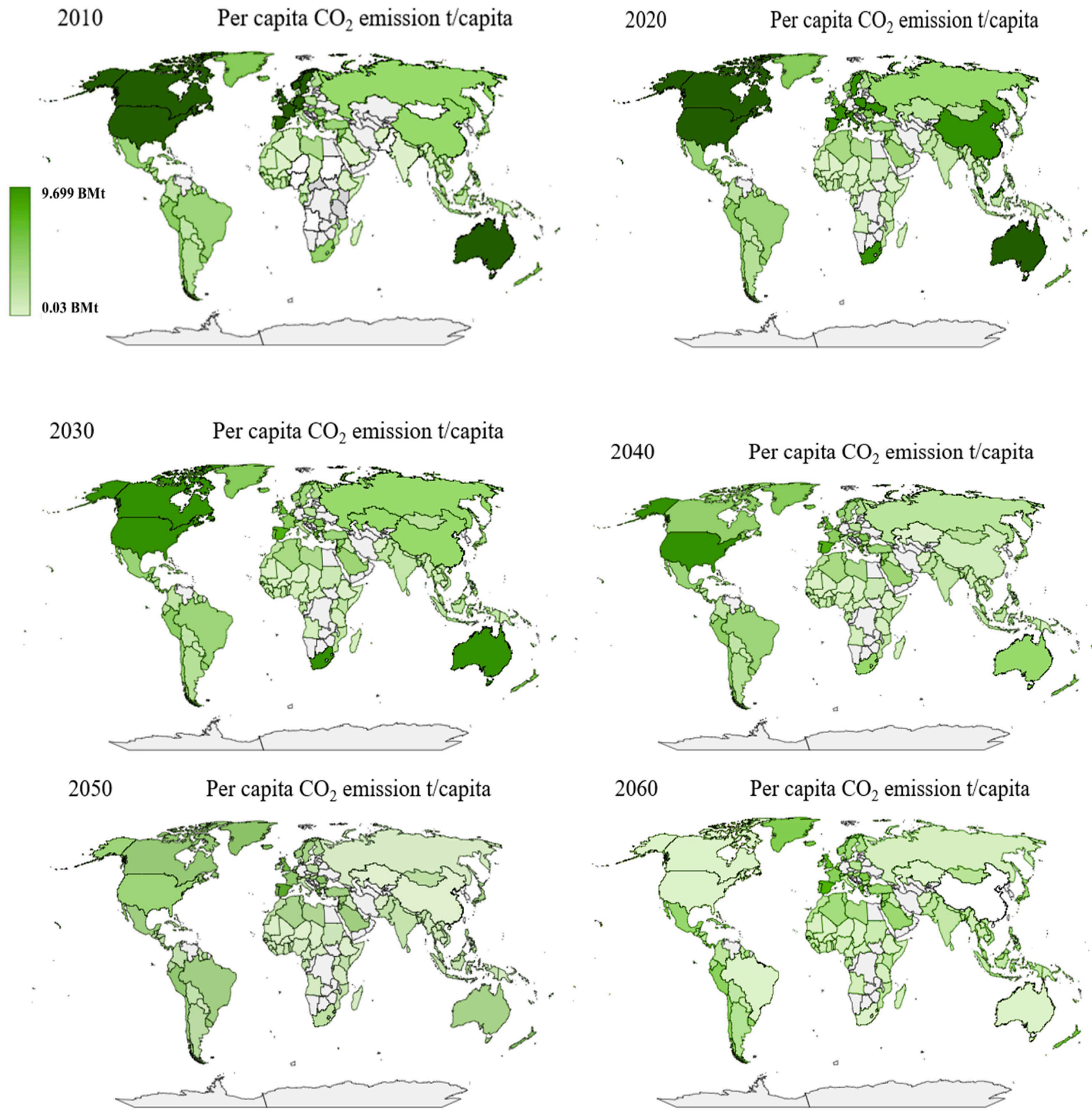

Fig. 12. Geographical expressions of CO_2 emission in a metric ton from 2010 to 2060. The variation of green color goes from a high to low which depicted the change in CO_2 emission over time.

forest open fields accounting for 1.12 BMt CO_2 emissions and the transportation sector contributing 1.35 BMt CO_2 emissions respectively.

The CO_2 mitigation strategies, emergency action plans, and clean air rules will reduce CO_2 emission from agricultural, forest, and transportation sector. This can be noticed in Fig. 12, the regions and countries become blurred from dark by 2030 to 2040 which shows the difference in emissions levels. Besides, in 2050 to 2060, it will be evident that the aim of net zero emissions will be attained, as CO_2 emissions would have decreased from 9.699 BMt to 0.03 BMt, notably in developed countries. Furthermore, underdeveloped countries have made significant strides toward zero emissions. The reduction in carbon emissions reached the significant level shown in Fig. 12 section 2060, with the United States emitting 0.46 t of carbon dioxide per capita and the Asia area producing 0.33t of carbon dioxide per capita in emissions. In addition, by the year 2060, regions such as Western Europe and North America will have implemented regulations on emissions.

4. Challenges, limitation, and future perspectives

Biohydrogen production from biomass residues offers a renewable and carbon-efficient pathway. Compared with other hydrogen production routes such as water electrolysis powered by renewables or steam methane reforming (SMR) with carbon capture and storage (CCS)biohydrogen differs in scalability, infrastructure requirements, and lifecycle emissions. It is particularly advantageous in regions with abundant biomass and limited electricity access, whereas electrolysis requires substantial renewable energy infrastructure and SMR with CCS depends on fossil fuels and carbon storage capacity.

Using agricultural and forestry residues holds great promise, but commercialization faces several challenges, including accurate assessment of residue availability and quality, feedstock transportation, technological advancement, economic feasibility, and environmental sustainability. Regional variations in biomass distribution influence CO_2 reduction potential, emphasizing the need for context-specific planning. Addressing these challenges requires interdisciplinary collaboration among researchers, engineers, policymakers, and industry stakeholders, as well as continued investment in R&D, technological innovation, and policy support.

Africa holds significant potential for forest residues, but realizing this requires overcoming infrastructure, technological, traditional biomass use, and policy barriers [67]. Similarly, in sub-Saharan Africa and parts of Oceania, decentralized biohydrogen production from locally available residues offers a low-cost solution. For example, agricultural residues in East Africa or forestry residues in Oceania could be converted into biohydrogen for local transport or power applications, reducing reliance on grid expansion [68]. Nonetheless, technical capacity and logistics remain key constraints. Policy effectiveness in advancing biohydrogen production from biomass residues varies by region. In developed economies, pricing instruments such as carbon taxes and subsidies effectively stimulate investment and innovation in residue-to-hydrogen technologies. In contrast, in developing economies, regulatory measures such as mandates on residue collection, restrictions on open burning, and renewable fuel quotas prove more impactful by directly mobilizing available biomass under limited market and financial capacity [69]. In Kenya, abundant maize and sugarcane residues face challenges from limited collection infrastructure and traditional biomass use, making regulatory measures and decentralized systems crucial [70]. In Australia, forestry residues are available but dispersed, and high transport costs limit feasibility, highlighting the need for policy incentives and localized conversion technologies [71]. In Germany, strong carbon pricing and subsidies, combined with mature infrastructure and advanced technology, enable large-scale integration of residues into biohydrogen production [72]. So, advancing biohydrogen production also requires adaptive research, improved data collection, and technology-based solutions for efficient feedstock collection, transportation, and utilization. Development of cost-effective machinery for residue handling and hydrogen production remains a key research priority, alongside government and institutional support through subsidies and incentives.

Techno-economic and environmental benchmarking of biohydrogen versus other clean hydrogen pathways is essential to identify the most cost-effective, sustainable, and scalable solutions for decarbonizing energy-intensive sectors. National and regional policy frameworks play a crucial role in this transition. For instance, China's 14th Five-Year Plan, the EU's Fit for 55 package, Japan's Basic Hydrogen Strategy, and the United States' Hydrogen Energy Earthshot demonstrate how targeted policies, financial incentives, and regulatory support can accelerate biohydrogen adoption. Finally, while fermentation technologies show promise for high-yield, environmentally friendly production, further research is needed to reduce costs and improve efficiency. The future of biohydrogen as a sustainable energy source and carbon mitigation solution depends on continued technological innovation, resource optimization, infrastructure development, policy support, and market deployment strategies. By addressing these areas, biohydrogen can play a significant role in transitioning to a low-carbon energy future.

5. Conclusion

This study demonstrates that agricultural and forest residues in major biomass-rich regions such as China, India, the U.S., Russia, Europe, and Brazil offer substantial potential for biohydrogen production, which could significantly reduce CO_2 emissions in agriculture and transportation by 2040–60. making the possibility become a reality, however, requires targeted strategies to overcome challenges in residue collection, logistics, production and sustainable supply chains.

Three key enabling steps are essential. First, regional biohydrogen hubs should be established in biomass-rich areas to distribute production, minimize transportation costs, and generate local employment opportunities. Second, decentralized gasification and hybrid technologies such as modular gasifiers coupled with biochemical conversion are needed to maximize residue utilization efficiency, provide flexible energy solutions, and enable gradual scaling through small to medium-scale systems. Third, digital residue tracking systems leveraging blockchain or AI can improve transparency, optimize residue availability mapping, and strengthen supply chain traceability, ensuring reliable and sustainable biomass flows.

Achieving these steps requires strong collaboration between governments, research institutions, and industry. For research, priorities include yield optimization, hybrid conversion pathways, and techno-economic analysis. For industry, scalable pilot and demonstration projects are necessary to validate technologies under real-world conditions. For policy, supportive frameworks such as subsidies, carbon credit mechanisms, and residue management standards are critical to incentivize adoption and ensure sustainability. If implemented, these measures could reduce CO_2 emissions from 9.698 BMt to as low as 0.03 BMt by 2060, positioning biohydrogen as a cornerstone of a more sustainable, resilient, and low-carbon energy future.

CRediT authorship contribution statement

Aqib Zahoor: Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nadeem Tahir:** Methodology, Funding acquisition. **Lingyu Tai:** Formal analysis, Data curation, Conceptualization. **Wenchao Ma:** Formal analysis, Data curation, Conceptualization. **Mingtao Hu:** Methodology, Investigation, Conceptualization. **Yajuan Yu:** Formal analysis, Data curation, Conceptualization. **Amanda Reichelt-Brushett:** Writing – review & editing, Writing – original draft. **Tapas Sen:** Writing – review & editing, Writing – original draft, Visualization. **Martina Damizia:** Data curation, Conceptualization. **Benedetta de Caprariis:** Data curation, Conceptualization. **Paolo De Filippis:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jaecs.2025.100410.

Data availability

Data will be made available on request.

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