ARTICLE

Benefit analysis of multi-approach biomass energy utilization toward carbon neutrality

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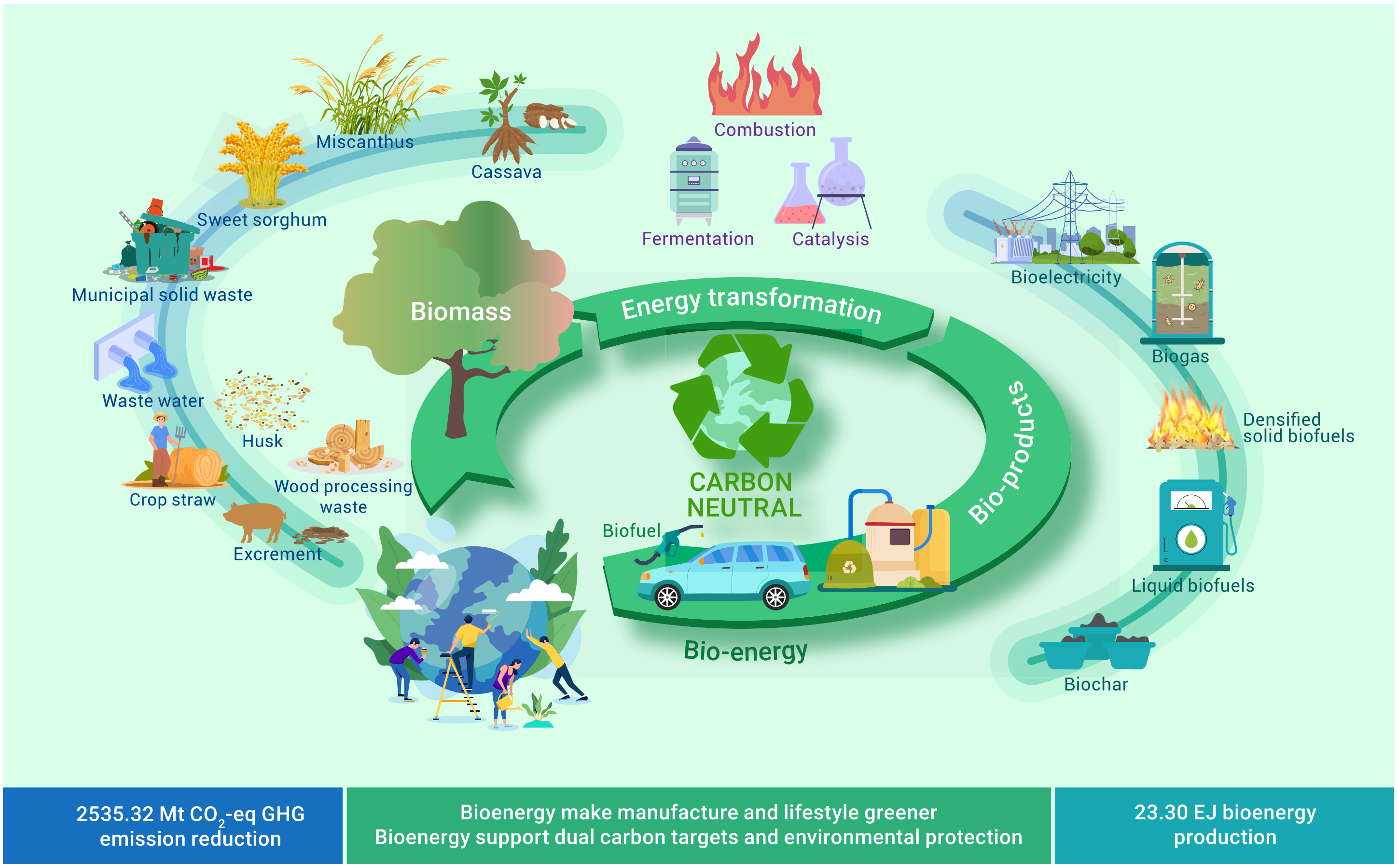
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Bioenergy accounting model with a multi-dimensional analysis is developed.
- Bioenergy potential takes up about 19% of China's total energy production.
- Bioenergy GHG reduction accounts for about 25% of China's carbon emissions.
- Bioenergy and GHG reduction potential are top in Guangxi autonomous region and Yunnan and Sichuan provinces.
- Bioelectricity is more effective in substituting for conventional counterparts.

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To reduce greenhouse gas (GHG) emissions, biomass has been increasingly developed as a renewable and clean alternative to fossil fuels because of its carbon-neutral characteristics. China has been investigating the rational development and use of bioenergy for developing its clean energy and achieving carbon neutrality. Substituting fossil fuels with multi-source and multi-approach utilized bioenergy and corresponding carbon reduction in China remain largely unexplored. Here, a comprehensive bioenergy accounting model with a multi-dimensional analysis was developed by combining spatial, life cycle, and multi-path analyses. Accordingly, the bioenergy production potential and GHG emission reduction for each distinct type of biomass feedstock through different conversion pathways were estimated. The sum of all available organic waste (21.55 EJ yr^{-1}) and energy plants on marginal land (11.77 EJ yr^{-1}) in China produced 23.30 EJ of bioenergy and reduced 2,535.32 Mt CO_2-eq emissions, accounting for 19.48% and 25.61% of China's total energy production and carbon emissions in 2020, respectively. When focusing on the carbon emission mitigation potential of substituting bioenergy for conventional counterparts, bioelectricity was the most effective, and its potential was 4.45 and 8.58 times higher than that of gaseous and liquid fuel alternatives, respectively. In this study, life cycle emission reductions were maximized by a mix of bioenergy end uses based on biomass properties, with an optimal 78.56% bioenergy allocation from biodiesel, densified solid biofuel, biohydrogen, and biochar. The main regional bioenergy GHG mitigation focused on the Jiangsu, Sichuan, Guangxi, Henan, and Guangdong provinces, contributing to 31.32% of the total GHG mitigation potential. This study provides valuable guidance on exploiting untapped biomass resources in China to secure carbon neutrality by 2060.

INTRODUCTION

Increasing worldwide concerns regarding energy demand and environmental issues, such as global warming, have encouraged the development of renewable energy.[1,2] Bioenergy, the world's fourth-largest energy resource, is a crucial component in the renewable energy mix owing to its green, low-carbon, and clean properties and substantial development potential.[3] The carbon emissions in bioenergy, an internationally recognized zero-carbon renewable fuel,[3] are re-sequestered by photosynthesis during biomass growth,[4–6] leading to a lesser CO_2-intensive fuel compared with fossil fuel. If coupled with carbon capture and storage (CSS) technology, such utilization could result in neutral or even negative carbon emissions.[7–9] Modern and efficient bioenergy use contributes approximately half of all renewable energy consumption (19.5 EJ), meeting 5.1% of total global final energy demand.[10] Global bioenergy production is expected to grow from 56 to 145 EJ in 2060 because of the increased role of modern bioenergy over traditional biomass usage.[2,11]

As the largest energy consumer and carbon emitter,[12–14] China has been shouldering the responsibility of addressing climate change and is committed to carbon neutrality. However, it is a country with predominant fossil fuel consumption,[15–17] rendering increasing concern among academia, government, and industry on how to achieve energy conservation and emissions reduction. Bioenergy has great carbon mitigation potential. The current bioenergy utilization in China could reduce approximately 218 Mt CO_2-eq[14] of carbon emissions.

With the global implementation of bioenergy with carbon capture and storage (BECCS) technology for electricity production, net sequestration of 2,500 Mt CO_2 yr^{-1} can be guaranteed for a 30-year evaluation period.[18] However, the technology may take years to mature.[19] Recently, a ready-to-implement biochar technology has attracted widespread attention,[19] and it is predicted that biochar systems can deliver global emission reductions of 3,400–6,300 Mt CO_2-eq yr^{-1}.[20] In China, if 73% of national crop residues are used between 2020 and 2030, the cumulative GHG reduction could reach 8,620 Mt CO_2-eq by 2050.[19] However, cost, technology maturity, feedstock supply, policies and regulations, market demand, and other factors are critical to determining whether these systems are competitive for biomass-based energy production.[2,21–23] BECCS and the production of biochar and biohydrogen are frontier technologies with considerable potential; however, they currently have high production costs.[2,19,20] Production of bioenergy such as liquid biofuels, biomass briquettes, and biogas are relative mature technologies in the market under the support of the government.[3,23] However, if biomass energy continues to play an important role in the drive toward carbon neutrality, cost and technology may no longer be future obstacles.[3,24–26]

China has abundant and diverse biomass resources[27–35] which are used in agriculture, energy, feed, construction, and the chemical industries.[29,35] With robust government support, the use of biomass energy has been rapidly increasing in China,[36] with the country becoming a global leader in bioelectricity production.[10] However, despite this, modern bioenergy development remains comparatively slow and even marginalized compared with that of other types of renewable energy.[37] For a low-carbon future, thoroughly assessing the availability of biomass resources, energy substitution, and the associated GHG mitigation potential is necessary. Although previous studies have emphasized biomass resources for potential energy use in China, most have focused on single species, case studies, and limited biomass types without comprehensive estimates.[4,8,38–40]

Focusing on biomass energy use and considering the existing knowledge gaps, this study aimed to build a comprehensive bioenergy accounting model with a multi-dimensional analysis, combining of spatial, life cycle, and multi-path analyses. Life cycle assessment method, GHG emissions inventory, spatial analysis method, and Monte Carlo simulation were synthetically utilized. We adopted the accounting model to quantify the potential of bioenergy substitution and associated GHG mitigation. The potential of carbon-neutrality-oriented GHG mitigation was first estimated based on a spatially comprehensive framework by combining multi-source and multi-approach bioenergy production. This research may provide geographically

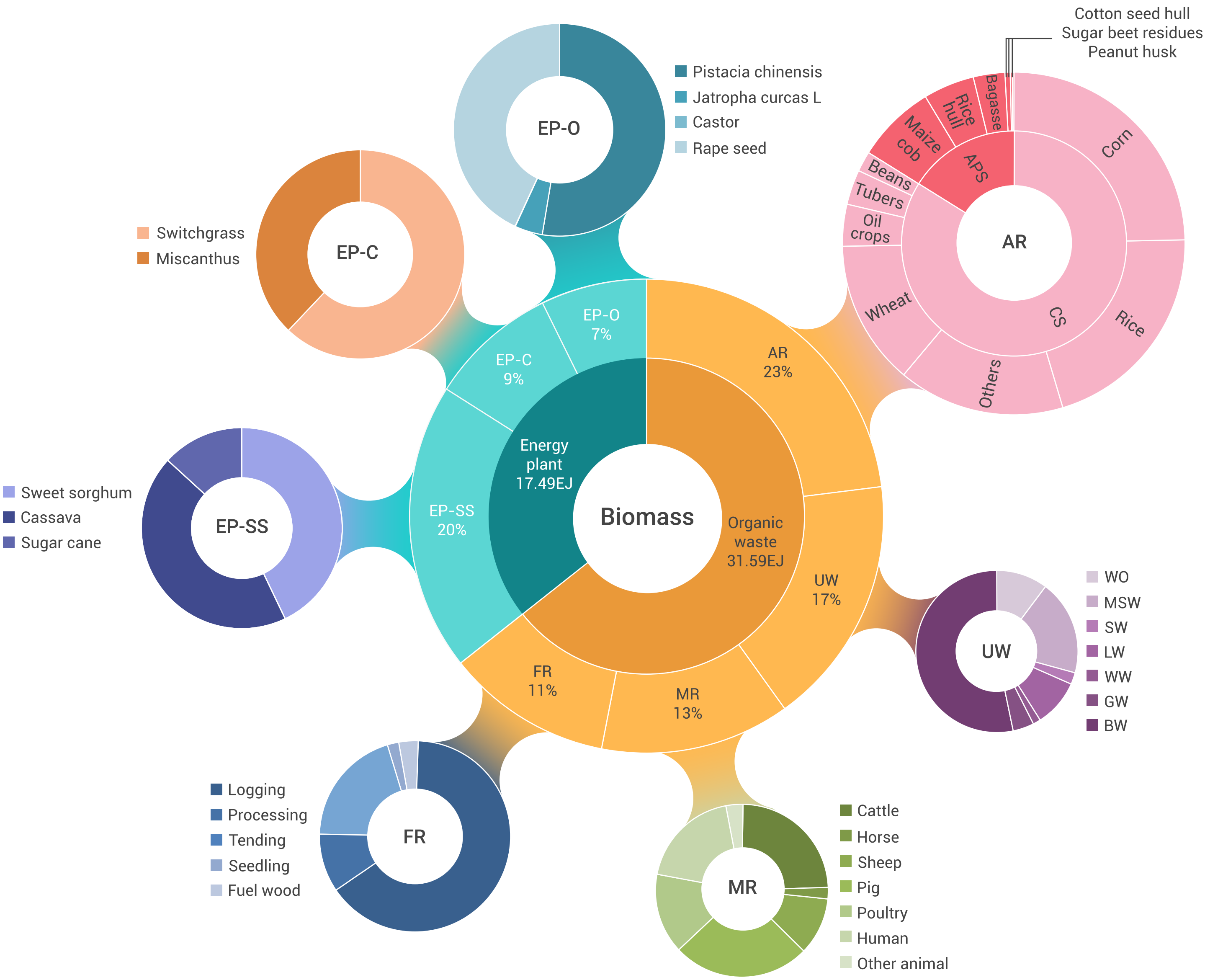

Figure 1. Collectable biomass resources and the composition in China (UW, urban waste; MR, manure residue; FR, forest residue; AR, agricultural residue; EP, energy plants; EP-C, cellulose type of energy plants; EP-SS, starch and sugar type of energy plants; EP-O, oil type of energy plants; CS, crop straw; APS, agro-industry processing residue; WO, waste oil; MSW, municipal solid waste; SW, sludge; LW, light industry waste; WW, waste water; GW, garden pruning waste; BW, woody building waste.)

customized information for decision-makers to help exploit China's bioenergy resources, achieve carbon neutrality, and facilitate the establishment of a clean and low-carbon energy resources census and an information-sharing platform.[8]

RESULTS

Composition and spatial distribution of biomass resources

The annual collectable potential of biomass resources in China was 49.09 EJ in 2015 (Figure 1), primarily captured from organic waste (64.36%) and energy plants (35.64%). The organic waste primarily comprised agricultural residue (11.30 EJ), urban waste (8.42 EJ), forest residue (5.52 EJ), and manure residue (6.36 EJ). Agricultural residue mostly comprised crop straw, being 5.2 times higher than the other agro-industry processing residue components. Corn, rice, and wheat were the three major crop straw types (70.35%). Urban waste included various types of solid and liquid waste, of which woody building waste accounted for the largest share (53.80%). Forest residue primarily comprised logging, tending, and wood processing residues (a total of 95.35%). Manure residue primarily comprised excrement from pigs, cattle, humans, and poultry, cumulatively amounting to 85.46%. Energy plants on marginal land primarily involved sugar and starch types (9.60 EJ). Sweet sorghum, cassava, and switchgrass species provided the largest biomass, cumulatively accounting for 62.93% of energy plant-produced biomass.

Biomass resources distributed in southwest China exceed those in other parts, and the top biomass provinces of Yunnan, Guangxi, and Sichuan provided 26.27% of the total collectable biomass resources (Figure 2A). Notably, Yunnan and Guangxi gained their high biomass resources because of the greatest contribution of energy plants (Yunnan 76.45% and Guangxi 50.89%). Conversely, provinces or municipalities in north and west China, such as Beijing, Shanghai, Hainan, Tibet, Tianjin, Qinghai, and Ningxia, in descending order, possess relatively low biomass (less than 0.4 EJ). Excluding biomass harvested from energy plants, Guangxi, Henan, and Shandong were the top three holders of biomass resources, with a collectable biomass of 2.30 EJ, 1.96 EJ, and 1.95 EJ, respectively. For biomass obtained from organic waste, agricultural residue was greatest in Guangxi, Heilongjiang, Shandong, Henan, and Jilin, accounting for 39.52%. Forest residue was primarily concentrated in Fujian (1.27 EJ) and Guangxi (1.03 EJ) because of abundant bamboo logging residue. Manure residue was sourced largely from Sichuan, Henan, and Shandong provinces (total of 23.9%) because of high population and abundant livestock. Urban waste was substantial in Jiangsu and Zhejiang (2.06 EJ), of which woody building waste contributed the largest share.

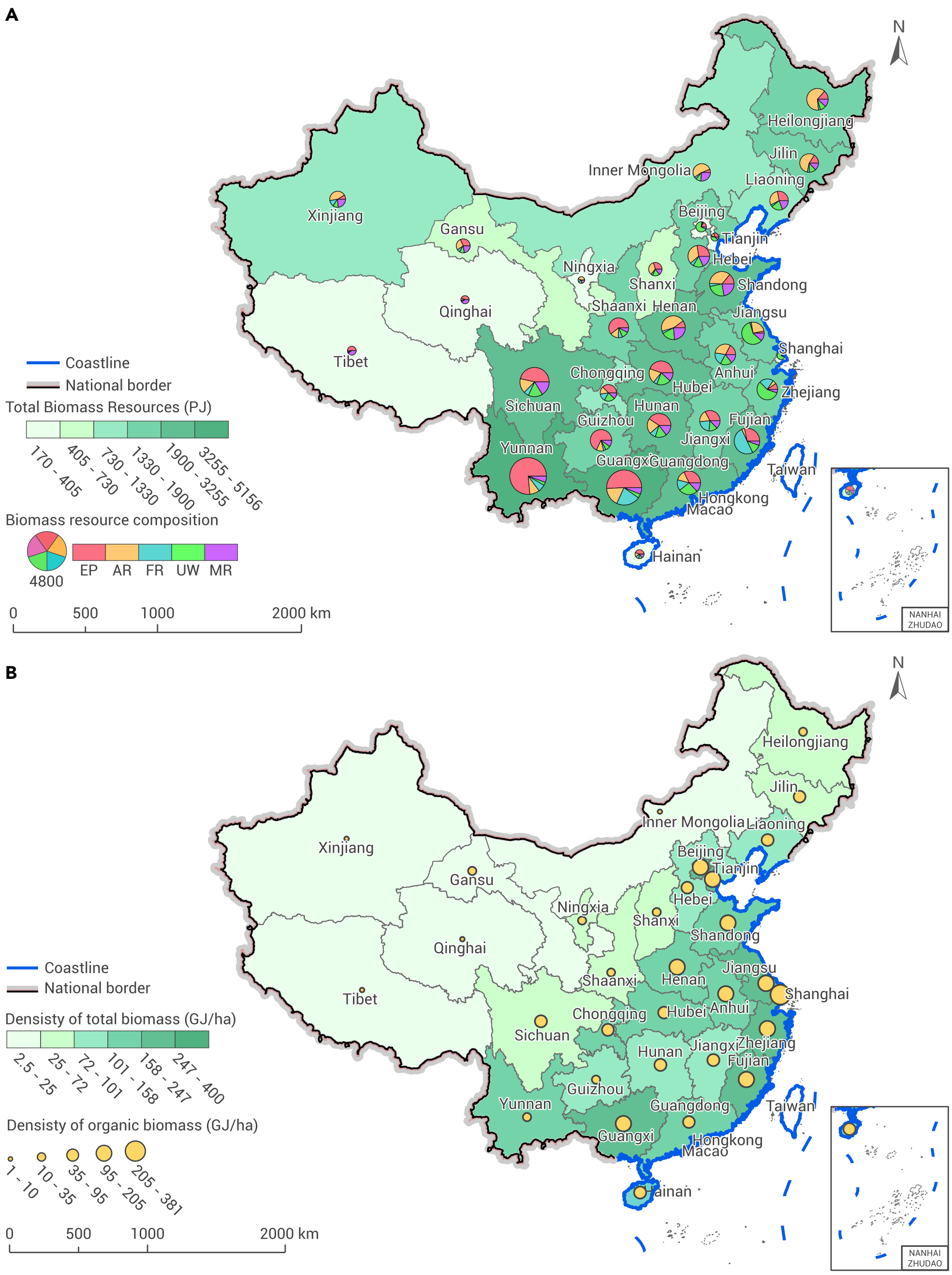

Figure 2. Provincial distribution characteristics of collectable biomass resources in China (A) Provincial distribution of collectable biomass resources and their composition. (B) Provincial distribution of biomass resources density.

The density of biomass resources in eastern China (>100 GJ/ha) was higher than that in western China. The Tibet, Qinghai, Xinjiang, and Inner Mongolia autonomous regions had relatively low density (<10 GJ/ha) (Figure 2B). When examining the biomass composition of all provinces, energy plants considerably impacted the ranking of provinces by their biomass resources. For example, Shanghai ranked the highest among all the provinces in resource density (380.58 GJ/ha) without considering energy plants in biomass. In contrast, Guangxi and Yunnan elevated from the fifth and fifteenth places to the fourth and ninth, respectively, with the contribution of energy plants, which are considerable assets of these two provinces.

Bioenergy production and energy conservation potentials

From the energy flow of land-biomass-bioenergy, the proportion of land use types combining wood land, agricultural land, marginal land, rural land, and urban land[41] indicated decreasing amounts; the collectable biomass of these land use types was 5.52, 11.30, 9.60, 6.36, and 8.42 EJ, respectively. Collectable biomass is only partially utilizable for bioenergy production, which decreased to 29.73 EJ because of loss and alternative utilization, such as agriculture, feed, construction, and the chemical industry (Figure 3). Accordingly, the final technical energy potentials of the carriers were 23.30 EJ, equivalent to 794.87 Mt of standard coal and 19.48% of the total energy production in China in 2020.

Under the assumption of bioenergy application, most biomass feedstocks were fermented for biohydrogen and ethanol (13.90 EJ), followed by gasification for biogas (3.74 EJ) and combustion for bioelectricity (3.52 EJ). Among all the bioenergy carriers, liquid fuels were the most promising types, comprising 2.99 EJ of ethanol (83.9 Mt) and 6.49 EJ of biodiesel (44.44 Mt), owing to vigorous support from the government.[4,8,40,42,43] Another two carriers that received widespread attention were biohydrogen and biochar, providing bioenergy of 5.18 and 2.82 EJ, respectively. Densified solid biofuel, the most widely used and commonly available on the market, had the potential to provide 2.49 EJ bioenergy (123.49 Mt). Biogas and bioelectricity, yielding 2.27 EJ (10.8 billion cubic meters) and 1.05 EJ (292 TWh), respectively, were ranked the lowest among all types (Figure 3). Each of the biofuel potentials is adequate to meet the development goals of biogas (8 billion cubic meters), bioelectricity (90 TWh), bioethanol (6 Mt), and biomass molding fuel (30 Mt) in the bioenergy 13th Five-Year Plan (2016–2021).[42]

From a feedstock source perspective, ethanol was primarily produced from energy plants (72.81%). Biodiesel was mostly synthesized from waste oil (84.23%). Biohydrogen, a biofuel with substantial potential, was largely made from energy plants and manure residue (cumulatively 64.38%). Densified solid biofuel primarily comprised agricultural residue and woody building waste (cumulatively 72.45%). Biochar, a carbon-rich stable solid, was primarily produced from manure residue (54.49%), the same source that had also been largely supplying biogas (53.89%). Bioelectricity sources were more diverse, primarily comprising woody building waste, agriculture, and forest residues (cumulatively 83.25%). Notably, the significant role of energy plants and waste oil in bioenergy production led to its highest potential in the Yunnan, Sichuan, and Guangxi provinces (Figure 4A).

After removing energy input in the life cycle of bioenergy production, the net energy was 16.89 EJ, mostly originating from biodiesel and biochar (51.65%). Notably, ethanol had negative net energy production, suggesting that the fossil energy input of ethanol production during the life cycle is greater than its yield, rendering ethanol production less efficient and feasible. Thus, Jiangsu, Shandong, and Henan provinces were ranked higher in net bioenergy production (3.37 EJ) than in bioenergy production because these provinces provided less biohydrogen and ethanol production (Figure 4B) that would otherwise decrease the net energy return. Apart from ethanol, the average unit net energy value in bioelectricity, biogas, densified solid biofuels, and biochar was higher than 1.00. When substituting biofuels for conventional fossil fuels, 43.29 EJ energy would be conserved, primarily by substituting biodiesel for diesel (13.08 EJ), biohydrogen for fossil-based hydrogen (10.05 EJ), and bioelectricity for coal-fired

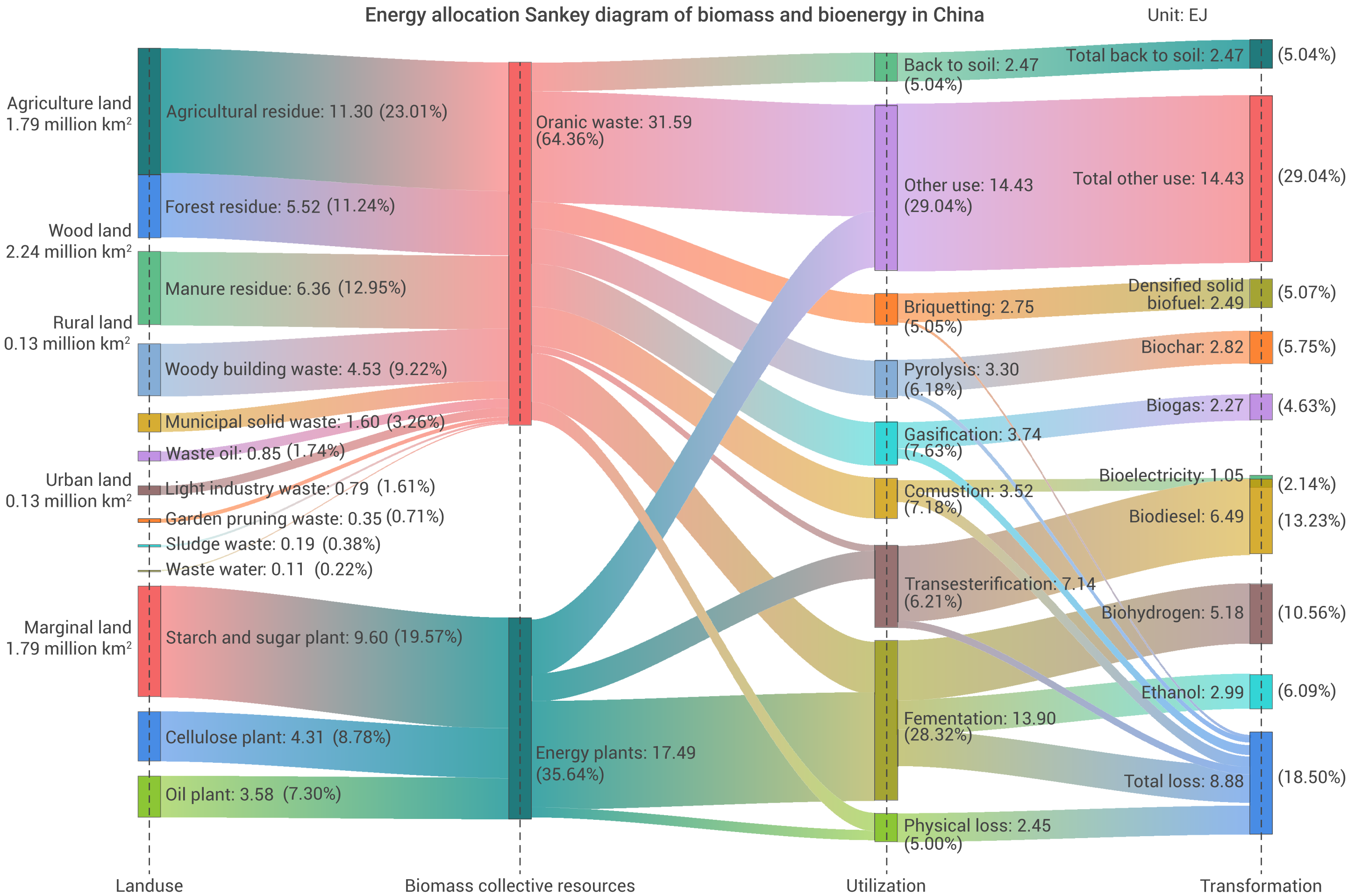

Figure 3. Energy allocation Sankey diagram of biomass and bioenergy in China (The areas of agriculture land, wood land, rural land, and urban land were cited by the study of Nie et al.[41])

power (6.08 EJ). The energy conservation unit value of bioelectricity was highest, with a value of 5.77, which was three to six times higher than those of other biofuel types. These results explain why the energy conservation value in Guangxi, Sichuan, and Yunnan was highest across China (Figure 4C). In summary, the large potential of biomass-related energy conservation should be credited to its low input demand rather than to the massive investments that fossil fuel production would otherwise require.

Analysis of GHG mitigation potentials

The potential of mitigating GHG emissions using bioenergy amounted to 2,535.32 Mt CO_2-eq in China (Figure 5). Biodiesel, biohydrogen, and biochar presented the greatest prospects for reducing GHG emissions, accounting for 62.04% of the total GHG reduction, owing to their substantial production potential. With a high unit value of net GHG reduction, bioelectricity (284.02 g/MJ) and densified solid biofuel (168.17 g/MJ) would potentially contribute 28.09% toward GHG reduction. Ethanol had GHG emission reduction potential of 99.03 Mt CO_2-eq because of its minimum production and lowest unit value of net GHG reduction among all carriers (only 11.67% of bioelectricity).

Unit GHG emissions of biofuels are comparatively lower than that of conventional fossil energy, particularly with bioelectricity that could provide the same amount of energy, which would otherwise require 12.5 times that of the conventional coal-fired power input. When considering the potential for both bioelectricity conservation and GHG reduction, bioelectricity would hypothetically be the optimal bioenergy carrier, unlike ethanol, the least desirable. From a life cycle perspective, the fuel utilization (FUST) and fuel production (FPST) stages had the highest GHG mitigation potentials with a value of 1,660.47 and 828.13 Mt CO_2-eq, respectively. GHG mitigation in FUST primarily originated from biodiesel (33.58%), biochar (27.62%), and densified solid biofuel (22.67%); however, in FPST, it mostly originated from biohydrogen (71.44%) and bioelectricity (28.13%) (Figure 5). This is because of their large corresponding bioenergy production and large unit GHG reduction and explains why manure residue, waste oil, woody building waste, and crop straw were ranked higher GHG mitigation potentials (accounting for 70.43%) than other biomass resources.

At a provincial scale, our findings indicate that Jiangsu province possessed the highest GHG mitigation potential (180.62 Mt CO_2-eq), accounting for 7.12% of China's total GHG mitigation potential (Figure 6). This is because biodiesel with high production, and bioelectricity with a high unit value, induced a relatively higher share (11.36%). Sichuan and Guangxi provinces have a high potential for GHG mitigation (taking up 6.4%) owing to their substantial biodiesel and biohydrogen production prospects. Conversely, Qinghai, Tibet, Tianjin, Hainan, and Ningxia had the least potential GHG mitigation, with each accounting for less than 1% of total potential mitigation.

Analysis of uncertainty and sensitivity

After 100,000 Monte Carlo simulations, we obtained the median values of collectable biomass resources of 49.09 EJ yr^{-1} (95% confidence interval, CI: 37.40–54.11 EJ), utilizable biomass resources of 29.37 EJ yr^{-1} (95% CI: 20.98–38.43 EJ), bioenergy production of 23.30 EJ yr^{-1} (95% CI: 17.86–36.80 EJ), and potential GHG mitigations of 2,535.32 Mt CO_2-eq yr^{-1} (95% CI: 1,008.28–3,666.83 Mt CO_2-eq). The estimations for the main biomass resources are kept within reasonable bounds of uncertainty as examined by the Monte Carlo model (Figure 7). The considerable discrepancies between different studies[8,39,44] might have resulted from different types of biomass resources and conversion coefficients incorporated in each study. Unlike previous research, this study considered all possible biomass resources, such as light industry waste, sludge, waste oil, energy plants, and human excrement,

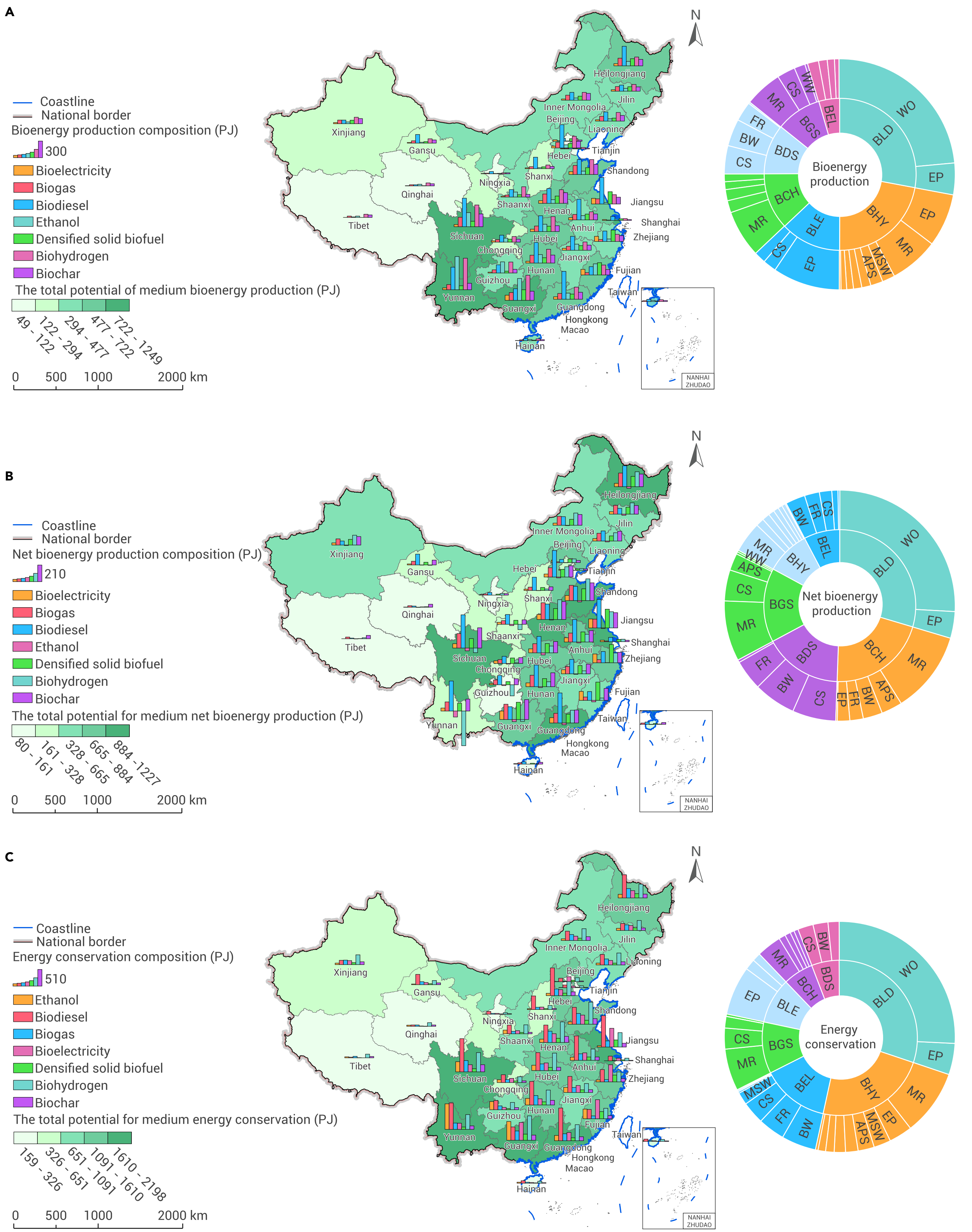

Figure 4. The total potential of China's bioenergy production, net energy production and energy conservation, and its composition (A) Bioenergy production and its composition. (B) Net bioenergy production and its composition. (C) Energy conservation and its composition. (BDS, densified solid biofuel; BEL, bioelectricity; BGS, biogas; BLE, ethanol; BLD, biodiesel; BHY, biohydrogen; BCH, biochar.)

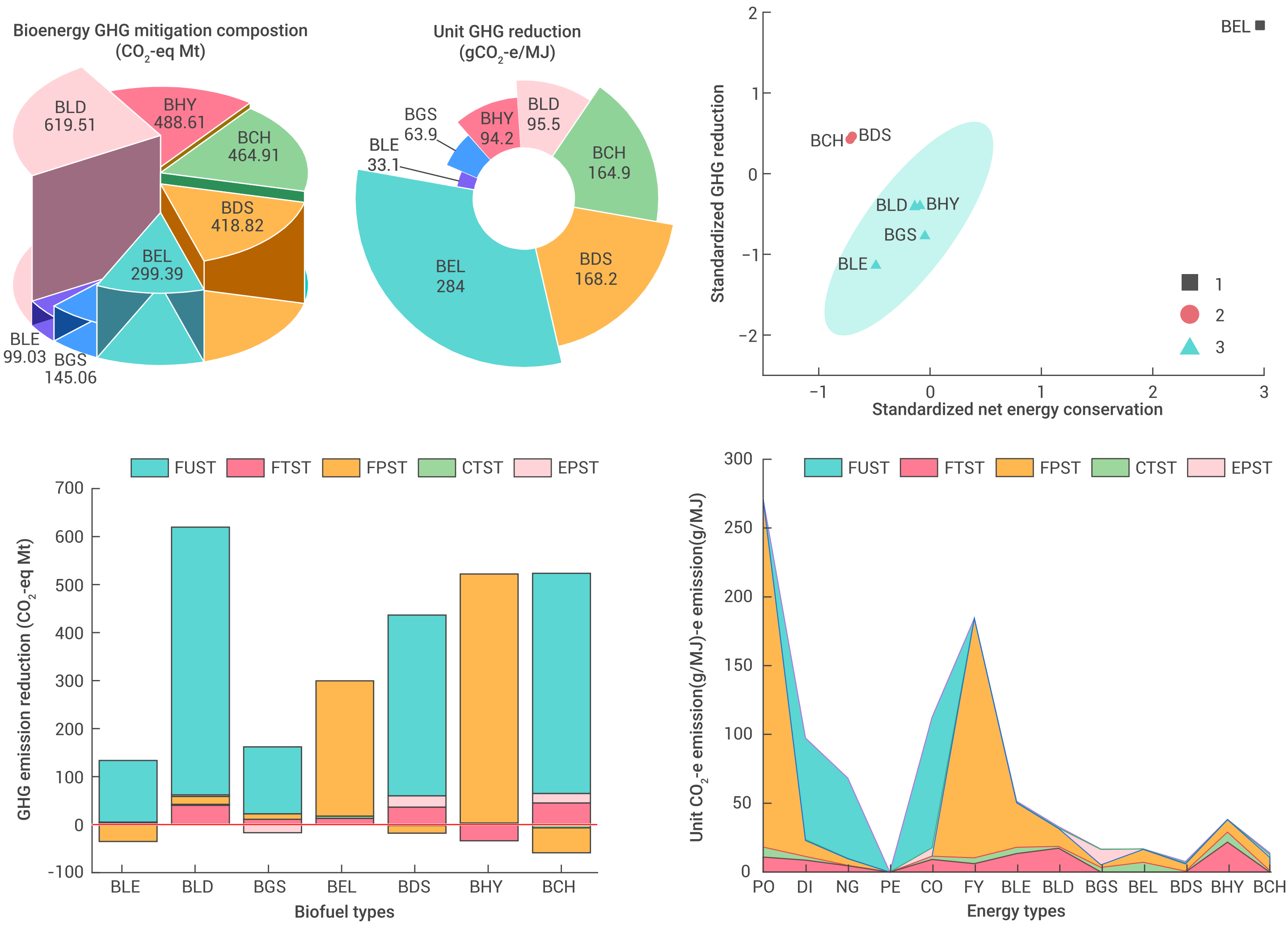

Figure 5. Bioenergy GHG mitigation potentials (PE, petrol; DI, diesel; NG, gas; PO, thermal power; CO, coal; FY, fossil-based hydrogen; EPST, exploitation/plantation stage; CTST, feedstock collection and transportation stage; FPST, fuel production stage; FTST, fuel transportation stage; FUST, fuel use stage.)

and developed a comprehensive accounting model with a multi-dimensional analysis to systematically evaluate the bioenergy potential in China, within a reasonable range.

Additionally, we conducted several sensitivity analyses to determine the influential variables on each type of biomass. The strongest sensitivity in biomass resources was for marginal land to energy plants (average 6.67%), followed by organic waste generation rates to urban waste (average 3.68%). The sensitivity of the bioenergy conversion ratio to bioenergy production ranged from 4.15% to 7.56%, indicating the importance of conversion technology to optimize bioenergy production. The greatest impact of fuel substitution on bioenergy carbon reduction was in bioelectricity. The net emission reduction deviated by 6.19% from the assumed baseline when substituting coal-fired power with bioelectricity, with 1.4 times for petrol replaced with liquid biofuel. These results suggest that optimizing bioelectricity production should be a priority rather than only boosting the yields of liquid biofuel. In summary, more on-site investigations should be conducted for marginal land, bioenergy conversion technology, and carbon emission parameters to facilitate emission reduction, given their considerable impact on reducing life cycle GHG emissions.

DISCUSSION

The GHG mitigation of China's bioenergy (2,535.32 Mt CO_2-eq) accounted for 25.61% of China's carbon emissions (9,899.3 Mt CO_2) in 2020.[41] This emission reduction could also take up 23.92% of the carbon peak (10,600 Mt CO_2 in 2023) if the target of 2°C is adopted in China, 18.29% with no constraint of CO_2 emissions (13,860 Mt CO_2 in 2040), and 19.50% in the scenario of achieving carbon neutrality in 2060 (8,600 Mt CO_2 with a rigorously applied 2°C target).[47] Internationally, this emission mitigation could contribute to 25.60% of the global carbon emission reduction to reach the goal set by the IPCC (medium 9,900 Mt in the "lower 2°C" scenario).[48] If China is fully compliant with the carbon reduction quota, setting a constraint on carbon peak, and achieving carbon neutrality,[45,46,49,50] bioenergy could contribute a 28.05% share toward achieving the national carbon reduction goal. Among those of all the provinces, the GHG mitigation potential of bioenergy in Guangxi plays the largest part in provincial carbon reduction (Figure 8), with the greatest bioenergy production (55.96%) being yielded from its ample biomass resources. In contrast, Beijing, Tianjin, Shanghai, and Hainan provinces contribute less to carbon reduction (<10%), because of their limited biomass resources (Figure 3). Therefore, to achieve carbon neutrality and emissions reduction targets, prioritizing provinces rich in biomass resources, such as Guangxi, Sichuan, and Jiangsu, should be considered for optimizing biomass development and utilization in China.

Although China possesses rich biomass resources and has great bioenergy development potential, problems still remain in large-scale industrialization and commercialization.[23] High costs, immature technology, low-profit margins, feedstock supply shortages, and chaotic market are major obstacles to bioenergy industry development.[2,21–23,55] Existing bioenergy technologies are not currently cost-effective compared with traditional fossil fuel, even to the photovoltaic and wind power renewable energy.[21,25] However, biomass is an important pathway toward the goal of carbon neutrality, with the expectation of achieving negative emissions due to its carbon-neutral characteristics.[3,18,19] The price of carbon will significantly increase with the increased pressure of achieving carbon peak and carbon neutrality, the launch of an emissions

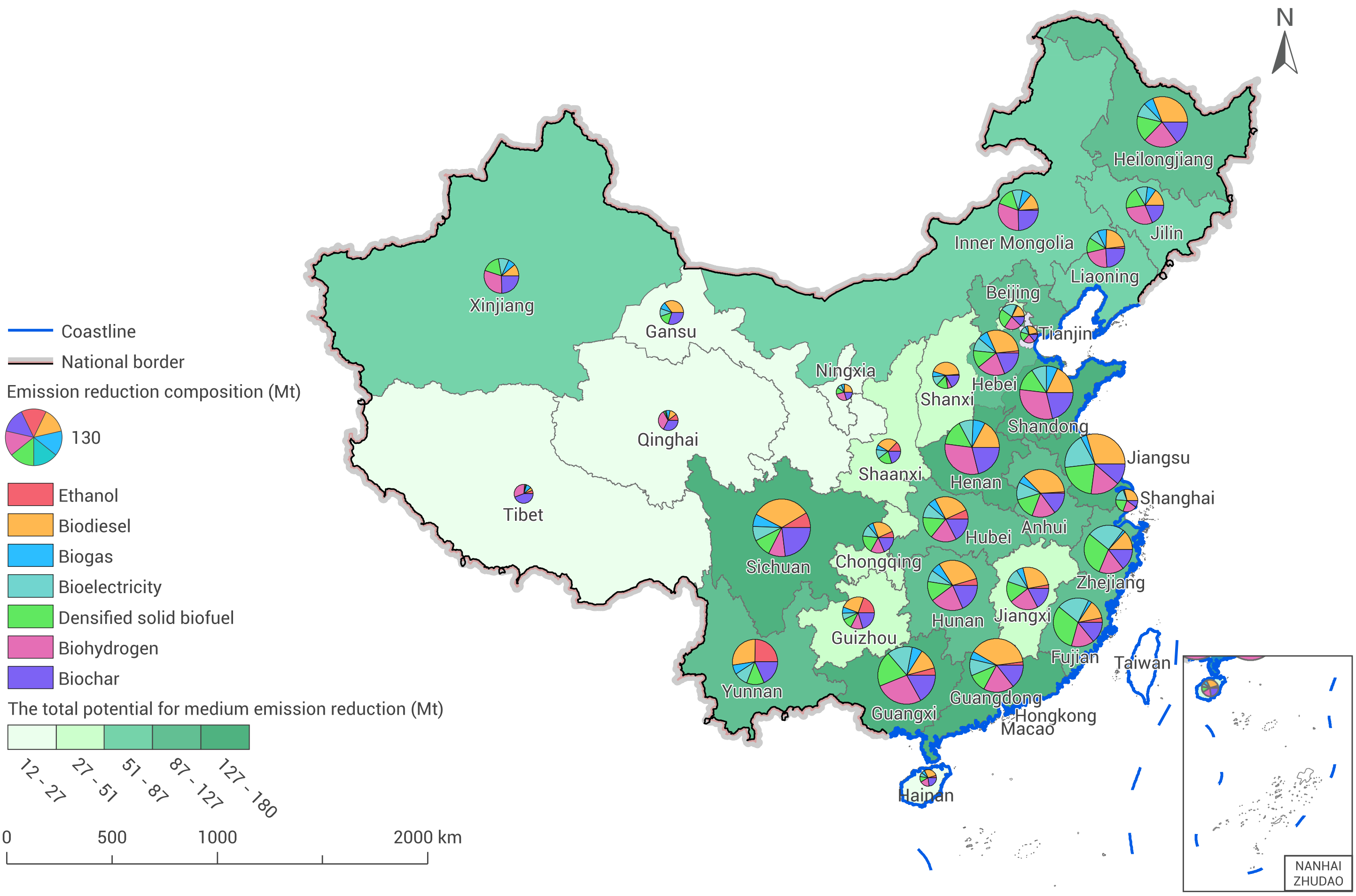

Figure 6. Provincial spatial distributions of bioenergy GHG emissions mitigation potentials

trading scheme, as well as the recently adopted EU Carbon Border Adjustment Mechanism.[24,25,56] With its great potential for emission reduction and the cost reduction driven by technological progress, bioenergy will be competitive with other fuels. For the effective long-term development of bioenergy industry in China, a series of initiatives should still be offered, such as implementing policy support, providing tax relief, offering specific subsidies, persisting in technology innovation, establishing an industrial standard system, opening the market, and accelerating commercialization.[2,55]

Based on the established multi-dimensional research framework, a comprehensive analysis of bioenergy and its capability of mitigating GHG emissions through spatial, life cycle, and multiple-path analyses were conducted via Monte Carlo simulation. Furthermore, the solution of various types of energy plants on marginal land without overlapping calculations and rational parameter assignments were investigated (Data S1). The valuable range obtained ensures that the assessments are beneficial for the government to develop policies. Under this framework, future research should strengthen economic, technical, and environmental impact analyses. Given the considerable potential of bioelectricity in GHG mitigation, future research should explore its application potential and limitations, such as mixing with coal-fired power to achieve negative emissions. Additionally, based on the regional characteristics of high biomass energy in the Yunnan, Guangxi, Sichuan, Henan, and Shandong provinces, future research should focus on highlighting the feasibility of biomass conversion in these provinces and their effect on regional dual carbon target realization when selecting more tailor-made bioenergy conversion pathways.

CONCLUSION

This study comprehensively evaluated the China's multi-source and multi-approach utilization of bioenergy potentials. It is estimated that the potentially collectable biomass resources could reach 49.09 EJ yr^{-1} (95% CI: 37.40–54.11 EJ yr^{-1}) in 2015, primarily originating from energy plants (35.64%), the organic wastes of agricultural residue (23.02%), and urban waste (17.15%), with the highest in Yunnan and Guangxi provinces. Based on our estimated GHG mitigation potentials of 42 feedstock-to-final conversion pathways of bioenergy production, China's GHG mitigation potential would be 2,535.32 Mt CO_2-eq yr^{-1} (95% CI: 1,008.28–3,666.83 Mt CO_2-eq yr^{-1}). Jiangsu, Guangxi, and Sichuan provinces were found to have high GHG mitigation potential. Although liquid biofuels were estimated to have the greatest applicable prospect in bioenergy production, attention should also be paid to bioelectricity because of its highest potential of mitigating unit GHG emissions. The enormous GHG mitigation potential of developing the bioenergy sector will significantly contribute to meeting the goals of carbon emission reduction and carbon neutralization in China and worldwide.

MATERIAL AND METHODS

Calculation of biomass resources, bioenergy production, and GHG mitigation potential

The collectable and utilizable potentials of biomass resources, including agricultural residue, forest residue, manure residue, urban waste, and energy plants, in China from 2015 were assessed. Multi-source and multi-approach bioenergy production was evaluated by multiplying the relevant energy conversion coefficient by the obtained utilizable potential of biomass feedstock. We defined the net energy, energy conservation, and net GHG reduction values to assess the energy-saving and GHG emission reduction effects of biofuel pathways.[57] Detailed information on the calculation of biomass resources, bioenergy production, and GHG mitigation is provided in Text S1. The main equations are as follows.

Biomass resources.

$$M_{C,i} = P_i \times W_i \times C_i \quad \text{(Equation 1)}$$

$$M_{e,i} = M_{C,i} \times R_i \quad \text{(Equation 2)}$$

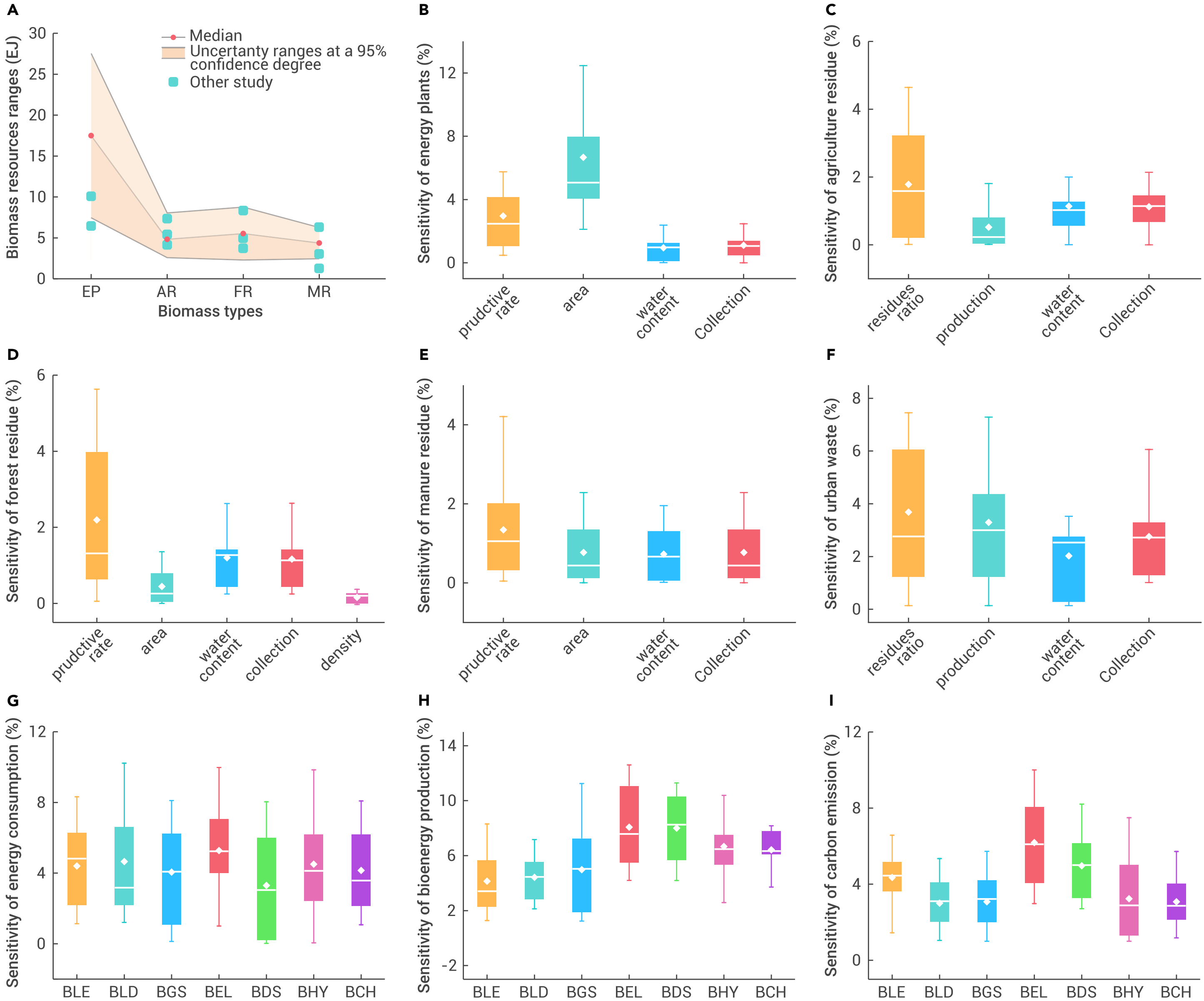

Figure 7. Uncertainty and sensitivity of bioenergy production potential (A) Uncertainties of the primary potentially collectable biomass resources in China in this study and comparisons with existing studies.[14,16,31,32,45,46] (B) Sensitivity of bioenergy production and GHG mitigation potential. (Diamonds and center lines represent mean values and 50th percentile, respectively. Boxes represent 25th to 75th percentiles, and bars represent 5th to 95th percentiles of sensitivity simulations.)

where $M_{C,i}$ is the amount of i type of collectable biomass resources, t/year; P_i is the amount of i type of biomass resources production, t/year; W_i is the dry matter content of i type of biomass resources; C_i is the collective coefficient of i type of biomass resources; $M_{e,i}$ is the amount of i type of utilizable biomass resources, t/year; and R_i is the ratio of i type of biomass resources used as energy.

Bioenergy production.

$$M_{bioenergy-j-i} = r_a \times M_{material-i} \times f_j \quad \text{(Equation 3)}$$

where $M_{bioenergy\text{-}j\text{-}i}$ is the amount of i type of utilizable biomass resource when making j type of bioenergy, t/year or m^3/year or MJ/year or kwh/y; r_a is the ratio of i type of biomass resource to make j type of bioenergy; $M_{material\text{-}i}$ is the amount of i type of utilizable biomass resource, t/year; and f_j is the bioenergy conversion factor, t/t or m^3/t or MJ/t or kwh/t.

GHG mitigation.

$$\mathrm{GRV}_j = \mathrm{GHG}_{LCA-baseline-j} - \mathrm{GHG}_{LCA-bioenergy-j} \quad \text{(Equation 4)}$$

$$GHG_{LCA-bioenergy-j} = \sum_{i,j=1}^{n} M_{bioenergy-j-i} \times \left(f_{eg-i-j} + f_{tg-i-j} + f_{pg-i-j} + f_{dg-i-j}\right), \quad \text{(Equation 5)}$$

where GRV_j is the GHG reduction value of j type of bioenergy, t/y; $GHG_{LCA\text{-}bioenergy\text{-}j}$ is the j type of biofuel pathway's GHG emission during the life cycle, t/y; $GHG_{LCA\text{-}baseline\text{-}j}$ is the responding baseline pathway of j type of bioenergy's GHG emissions during life cycle, t/y; $f_{eg\text{-}i\text{-}j}$, $f_{tg\text{-}i\text{-}j}$, $f_{pg\text{-}i\text{-}j}$, and $f_{dg\text{-}i\text{-}j}$ are GHG emission coefficients at biomass feedstock plantation stage, feedstock collection and transportation stage, bioenergy production stage, and bioenergy transportation stage, respectively, when using i type of biomass material to make j type of bioenergy, t/t or t/m^3 or t/kwh.

Data collection and processing

Basic biomass-related data were collected from the China Statistical Yearbook, China Statistical Yearbook on Environment, China Construction Statistics Yearbook, China Forest Statistic Yearbook, and the China Light Industry Yearbook. Missing biomass data were collected from other related reports or calculated based on reasonable assumptions. Energy consumption and GHG emission parameters were primarily acquired from published literature and databases. Through Monte Carlo simulation, the uncertainty estimations were separately applied in biomass resources, bioenergy production, and GHG mitigation models separately, which included more than 100 key variables and factors in bioenergy production (see supplemental information). These variables were classified into eight categories according to their attributes: yield/area, waste production coefficient, water content, collection

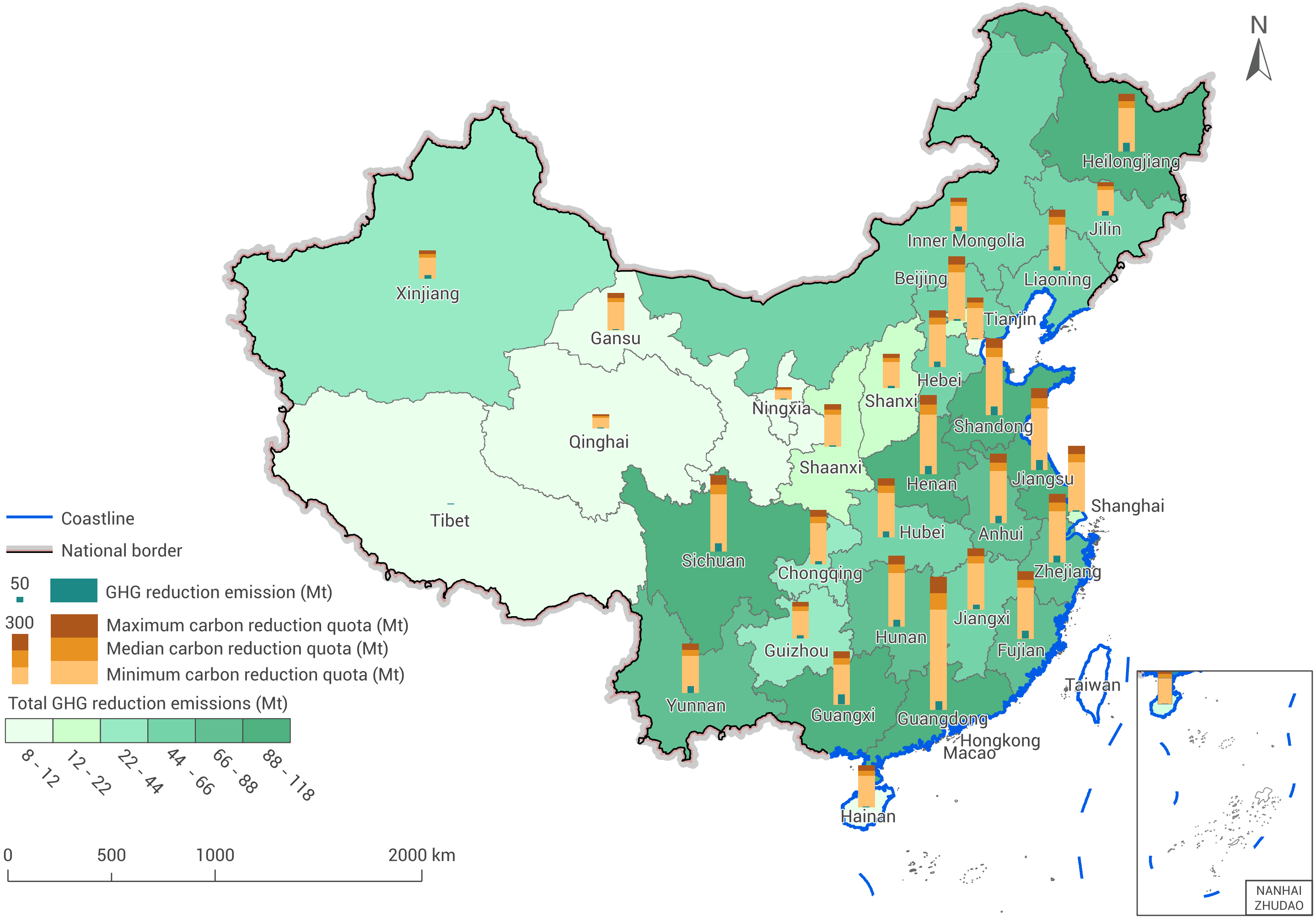

Figure 8. The roles of bioenergy in provincial carbon emissions reduction quota under the background of carbon peak and carbon neutrality (Provincial carbon emissions reduction quota derived from the difference between simulated national carbon peak and carbon-neutral emissions multiplied by the proportion of simulated provincial carbon emissions quotas. Citing the studies of Wang et al.[51]; Kong et al.[13]; Chen et al.[12]; Fang et al.[52]; Zhang et al.[53]; Zhou et al.[54])

coefficient, energy utilization ratio, bioenergy production rate, energy consumption, and GHG emissions. The implications for estimating potential bioenergy were set within the range of ±5%. Detailed information on data collection and processing is provided in Text S2 and the supplemental information.

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AUTHOR CONTRIBUTIONS

J.W. prepared, reviewed, and edited the manuscript with assistance from J.Fu, Z.Z., F.X., and F.W. J.W. performed the analyses with support from J.Y.F, Z.Z., L.B., and G.L. on analytical approaches and chart. J.W., Z.Z., J.F., Y.Y., and Q.H. curated the datasets. L.B. and S.W. developed the code and performed the simulations with support from J.W., Z.Z., and J.F. on datasets. F.X., F.W., and D.J. conceptualized and supervised the study.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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