

# Marginal lands for bioenergy in China; an outlook in status, potential and management

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## Abstract

Energy consumption and CO<sub>2</sub> emissions have been increasing continuously over the past few decades in China and there is a pressing need to replace the fossil fuel-based economy with an efficient low-carbon system, tailor-made to future requirements. China is starting an energy transition with the aim of building an energy system for the future. China has made tremendous progress in increasing the amount of renewable energy and reducing the cost of renewable energy over the last 20 years. According to the 14th 5 year plan, China aims to incorporate 20% of renewable energy to the primary energy mix and attain 27% reduction in CO<sub>2</sub> emissions. Bioenergy crops constitute a significant proportion of biomass-based bioenergy and have recently been promoted by the Chinese Government to help overcome food and fuel conflict. Steps are being taken to promote bioenergy crops on marginal lands in China, and various regions across the country with soil marginality have been evaluated for bioenergy crop cultivation. The present paper reviews the status of bioenergy in China and the potential status of marginal lands from different regions of China. It also elaborates on some of the policies, subsidies and incentives allocated by the Chinese Government for the promotion of biomass-based energy. Land management and plant improvement strategies were discussed, which are effective in making marginal lands suitable for bioenergy crop cultivation. Managing planting strategies, intercropping and crop rotation are effective management practices used in China for the utilization of marginal lands. A national investigation is desirable for creating an inventory of technical and economic potential of biomass feedstocks that could be planted on marginal lands. This would assist with highlighting the pros and cons of using marginal lands for bioenergy production and effective policy making.

## KEYWORDS

bioenergy, China, feedstock, marginal land, policy, subsidies

## 1 | INTRODUCTION

China has been undergoing tremendous economic growth over the last four decades and efficient policies by the

Chinese Government have moved approximately 750 million people out of extreme poverty (WorldBank, 2017). Such huge economic growth coupled with an industrial revolution led to high energy demand and consumption over time. Currently,

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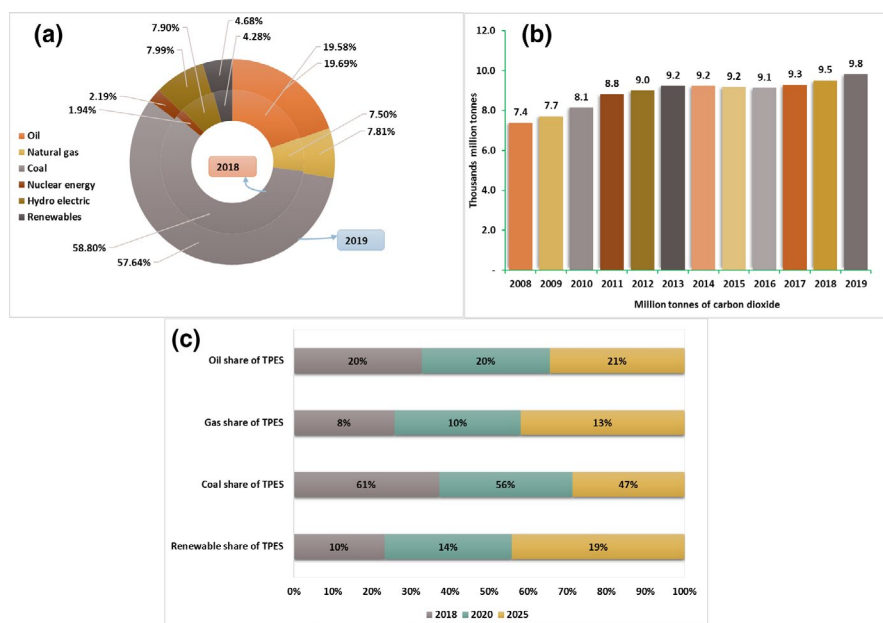
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the industrial sector in China consumes a larger proportion (about 60%) of total primary energy, which is higher than any other country in the world (NSB, 2018). According to a Reuters report that analysed the first 5 months of 2020, China brought in 148.71 million tons of coal, up 16.8% from the same period last year. Although residential coal consumption has reduced over the past couple of years due to high industrial growth, coal consumption increased by 1% and jumped to 3.84 billion tonnes in 2020 (NBS, 2018). Also, since 2017, coal consumption for power generation has increased by 8% (CNCA, 2018). Likewise, crude oil and natural gas consumption also increased by 6.5% and 18% in 2018, respectively, and oil consumption jumped to 639 million tonnes, which is 3.4 times higher than domestic output. The oil import was 2.4% higher than in 2018 and Chinese dependency on imported oil has now reached 72%. A recent report suggests that Chinese natural gas consumption has increased by 45.3% (NBS, 2018) and China has imported 1.9% (40.12 m tonnes) more natural gas in the first half of 2020 than in 2019. Researchers expect China's natural gas import volume and import dependence to continue to grow (Li et al., 2016; Lin & Wang, 2012; Wang et al., 2016; Figure 1a). China is heavily dependent on foreign oil supply, importing oil from more than 10 countries, of which Russia, Saudi Arabia, Angola, Oman, Iraq, and Iran are the major suppliers. Oil import from five of these six countries is seaborne and passes through the Strait of Malacca (Shaikh et al., 2016). There is a spatial difference in oil and coal production and utilization as many domestic oilfields are present in the western and northeastern areas of the country, but these areas have less industrial oil consumption than southeastern coastal regions. Likewise, the southeastern coastal regions of China have high oil demand due to them being the industrial hub of the nation, but they lack domestic oil resources and rely on maritime import. The

Chinese Government is interested in energy cooperation and development across its borders, in addition to marine transport which accounts for about 80% of total import. China has developed three onshore strategic energy routes by constructing cross border pipelines. These include Kazakhstan–China, Russia–China and Myanmar–China (Chen & Fazilov, 2018; Muhammad & Long, 2020).

Energy independence has a vital role not only in sustainable development of a society but also in policy making, international relations and cooperation. Sufficient energy resources are fundamental for a country's progress. Moreover, a country must ensure energy security for the present as well as for the future to continue to achieve significant growth and development (Nabiyev, 2018; Zou et al., 2020). Energy demand and environmental impact of coal and fossil fuel burning are a preference of China's national security and policy legitimacy. China is revising its land and renewable energy development policies to promote sustainable development of its small and large communities. Currently, China is developing strategies to attain energy independence by 2050 and this dream can only be fulfilled by growth of the state's power. With emergence and utilization of new and advanced technologies of crop, land and technology management, China could attain its energy independence goal (Zou et al., 2020).

Fast economic and population growth coupled with high CO<sub>2</sub> and other greenhouse gas emissions are two main reasons that are pushing China for sustainable energy development. China hosts about one-fifth of the total global population with a fast-growing GDP of over 9%. Over the last two decades, China has undergone tremendous economic growth, which has led to doubling of the consumption of energy resources, and now China is among the world's top energy consumers (CEPPEI, 2018). Thus, for a country with



**FIGURE 1** (a) Share of different fuel types in primary energy consumption in China during 2018–2019 (b) CO<sub>2</sub> emission in China due to burning of fossil fuels during 2006–2018 (c) Share of different energy sources to primary energy supply in China during 2018, 2020 and 2025. (TPES: Total primary energy supply)

such intensive economic growth, the search for new sources to fulfil current and future energy demand in a sustainable manner is indispensable. This will help in the social uplift of communities living in China as well as provide macroeconomic and raw material security to the state (Althageb, 2017; BioFuels, 2019; Zhang & Lis, 2020).

According to recently released official economic data, China is unable to control CO<sub>2</sub> emissions, since a 2.6% increase in CO<sub>2</sub> emissions was recorded during 2008–2019 (Figure 1b) and low carbon sources accounted for only 35% of the increase in energy demand (BP, 2020). This share will have to reach 100% or more for emissions to peak and decline, especially as the focus on energy security limits the scope for switching from coal to gas and oil (IEA, 2020; NBS, 2019). Various regions of China differ considerably in their growth, energy utilization, and CO<sub>2</sub> emissions, for example, eastern regions of China have high energy consumption coupled with high CO<sub>2</sub> release compared to the central and western regions (Dong et al., 2018; Feng & Wang, 2017). Thus, different policies for different regions of China should be formulated and implemented in order to effectively control CO<sub>2</sub> emissions.

An estimate shows that in China, about 19% of land area is affected with soil erosion, about 75% of lakes are polluted, and 15%–20% of the country's species are endangered (Liu & Diamond, 2005). Climatic change has also pronounced effects on ecosystem structure and functioning coupled with multiple economic loss (CAEP, 2014). The mean annual temperature has increased by 1.0°C over the past three decades which is higher than the global average (Wang et al., 2010).

Furthermore, the pattern and spatial distribution of rainfall has also significantly changed over the years although no significant alteration in annual precipitation has been observed as a whole (EC-TCNARCC, 2015; Wang, et al., 2010). Further intensification of this climatic scenario is predicted in the upcoming years. The economic losses caused by the burning of fossil fuels in China are shown in Table 1.

Bioenergy production has increased in China after emergence of renewable energy law in 2007. By 2020, bioenergy accounts for approximately 14% of total primary energy of the China while in 2025, this contribution will rise to 19% (CNREC, 2019) (Figure 1c). Owing to the limited cultivatable land area, China has implemented a national land policy that enforces sustainable and planned use of land resources. To prevent further squeezing of cultivatable land, China is promoting the cultivation of non-grain feedstock for bioenergy production on marginal lands. Since 2007, the Chinese government has prohibited cultivation of bioenergy crops on land that is being used for cultivation of food crops to avoid food insecurity. A study demonstrated that growing energy crops on crop land could increase food prices by about 0.1% (Weng et al., 2019) while planting energy crops on marginal land could enhance non-grain feedstocks by 10% and save about 0.217% of croplands (Tang et al., 2010; Zhuang et al., 2011). Thus, China needs to promote non-grain feedstock on marginal land in order to achieve its energy independence, as well as to prevent food insecurity and environmental damage.

In the early 1990s, renewable energy in China was only developed to fulfil shortage of small-scaled agricultural fuels and thus policies at that time were focused on construction

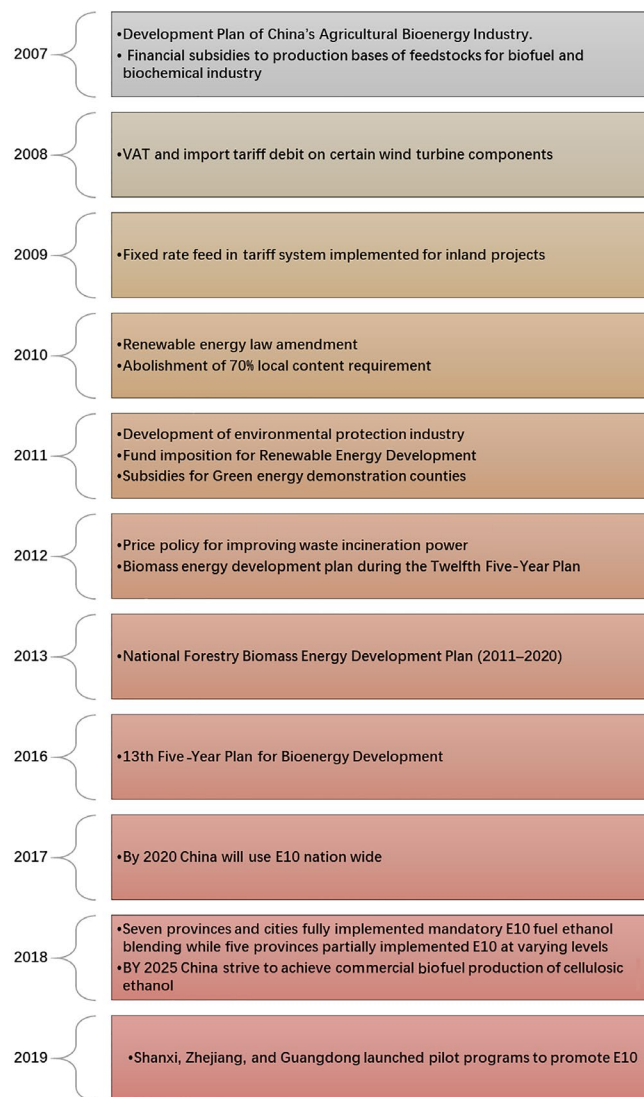
**TABLE 1** Economic Cost for Burning Fossil Fuels in China (CAEP, 2014)

Environmental external cost	Billion (CNY)	Environmental external cost	Billion (CNY)
Health loss from coal induced air pollution	267	Clean cost	3.41
Health loss of coal mine workers	93.4	Coal mining sewage treatment	3.14
Timber loss	53.07	Gangue land use	1.43
Reduction of crops	50.39	Gangue self-burning loss	0.97
Environmental damage from railway transportation	42.57	Local resident emigration	0.65
Underground water damage	34.42	Environmental loss of agriculture land	0.14
Soil and water run-off	20.07	Dispersion of coal dust	0.13
Coal loss during railway transportation	10.67	Planting cost	0.12
Coal loss during uploading	9.32	Grassland degradation	0.1
Coal loss during unloading	8.72	Biodiversity loss by deforestation	0.05
Land sink	6.68	Soil damage by gangue	0.01
Ecology loss by deforestation	4.34		

and strengthening of rural energy. The specialized policies or guidelines for the development of renewable energy and environmental regulation evolved during the 1990s through to 2005, and among them, a major breakthrough was the development of the renewable energy law in 2005, which was later amended in 2007. After the passing of this law, various regulations were adapted to promote bioenergy at a national scale, yearly targets and mandates were set, and many incentives and feed in tariffs were introduced (Schuman & Lin, 2012). Afterwards, renewable energy production and promotion was incorporated into a series of 5 year, medium and long-term plans. This uplifted bioenergy in China as incorporation of bioenergy production in China's 5 year plan produced more effective results than other laws. A recent example is due to these efficient policies and regulations, China has achieved its renewable energy target set in the 13th 5 year plan well before 2020 (NDRC, 2017). Many other laws for bioenergy promotion and environmental regulation and protection were brought into action. A Clean Energy Consumption Action Plan was issued in 2018 for better utilization of available renewable energy resources and to reduce waste. For each region of China, minimum targets for renewable energy consumption were set in order to solve power integration problems in 2020 (NDRC, 2018). To cope with environmental constraints caused by the burning of fossil fuel, the Chinese government has introduced a farmland protection policy and the law of land administration. The objectives of both were to facilitate land storage and reforestation as well as to improve the quality of the environment. The State Council of China set a limit of 120 Mha of cultivable land and imposed quintupled tax on cultivatable land if used for non-food purposes and forbidden use of grains and green grain crops for biofuel production after 2007 (Zhao, 2018). The progress in bioenergy policy during the last decade is shown in Figure 2.

## 2 | INCENTIVE AND INITIATIVES TO PROMOTE BIOENERGY FEEDSTOCK ON MARGINAL LAND

Various soil and environmental characteristics can be used to define soil marginality, for example, marginal soil has poor quality water or may be drought or salt affected, it may have poor soil properties, undesired texture and topology, a steep slope, compactness, imperfect drainage and may have adverse climatic conditions with low or no potential for food crops. Many definitions for soil and land marginality were put forward, but these differ from one area to another and also for one crop to another. Generally, marginal lands include contaminated brownfields such as lands affected by soil pollutants like heavy metals and pesticides (Smith et al., 2013), agricultural lands with low productivity, degraded lands (Tilman et al., 2006) and lands used to dispose city or industrial waste



**FIGURE 2** Evolution of bioenergy policy in China during 2007–2019. VAT: Value added tax

(Nixon et al., 2001). Thus, food production from marginal land is not possible till effective management practices are employed. China is focusing on the use of marginal lands for bioenergy production and employing many management and economic policies to reduce marginality and to promote bioenergy feedstock production on these lands. Although the Chinese government has employed many incentives for bioenergy production from food-based feedstock, a clear policy about the promotion of non-grain feedstock on marginal land is still lacking (Chen et al., 2016). Many incentives were offered by the Chinese government to promote bioenergy feedstock. A renewable energy development fund was established to support renewable energy producers and offer them special subsidies (MOF, 2011). Generally, bioenergy subsidies offered by the Chinese government can be divided into front end subsidies supporting energy crop production, promotion and rural development, and backend subsidies that facilitate



the industry and development sector (Figure 3). Specifically, bioethanol-based subsidies can be either fiscal subsidies offering support to energy-oriented enterprises, subsidies for feed-in engineering of biomass and subsidies for operation and maintenance of independent power generation systems (MOA, 2007). Similarly, in 2014, a notice for exemption of excise tax and reimbursement of value added tax was issued for bio-based fuel ethanol production.

Plantation of oleaginous nut-bearing plants was performed across many provinces of China by the State Forestry Administration comprising of an approximately 800,000 ha area with capacity of producing 6 million tons of biodiesel in order to promote feedstock for biodiesel production (Zhao, 2015).

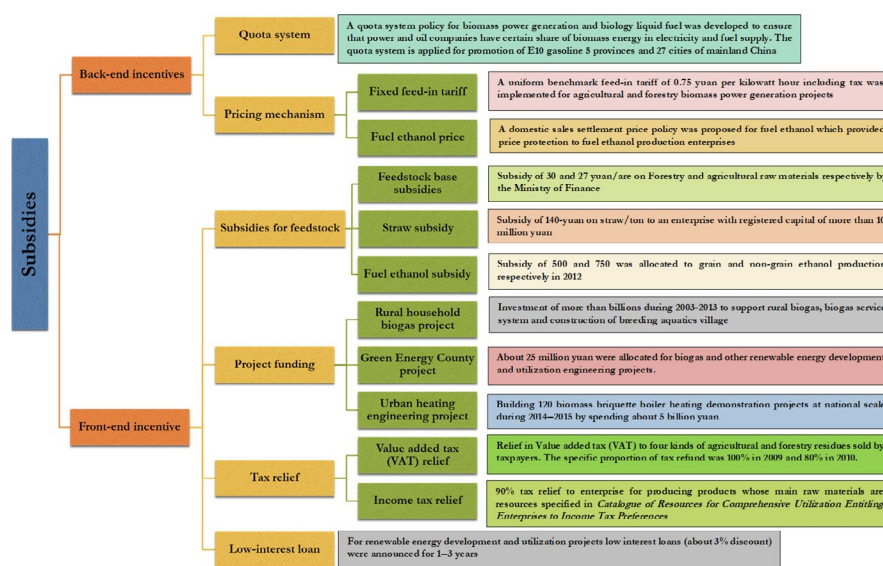
Many problems including expensive reclamation of marginal land, extra expenses on transport of feedstock to production plants and limited irrigation facilities hinder promotion of non-grain feedstock produced on marginal lands (Qiu et al., 2012b; Zhuang et al., 2011). Thus, for effective management of marginal land in addition to identifying the exact reason for marginality based on economic factors, soil health and environmental criteria, a detailed review of the existing soil, water and agriculture policies to promote energy production special incentives must be conducted and offered to stake holders for efficient promotion of non-grain biofuels (Qiu et al., 2012a; Yu et al., 2019). Furthermore, the lengthy and time-consuming process of approving subsidy payments that involve multiple institutions needs to be shortened for investors to get maximum benefit (ICE, 2018).

Conversion technologies are vital for promotion of non-grain feedstock promotion as these are key challenges for commercial biofuel producers (Qiu et al., 2012b). In China, ethanol production from cassava, sweet sorghum and sweet potato accounts for more than 70% of total production cost

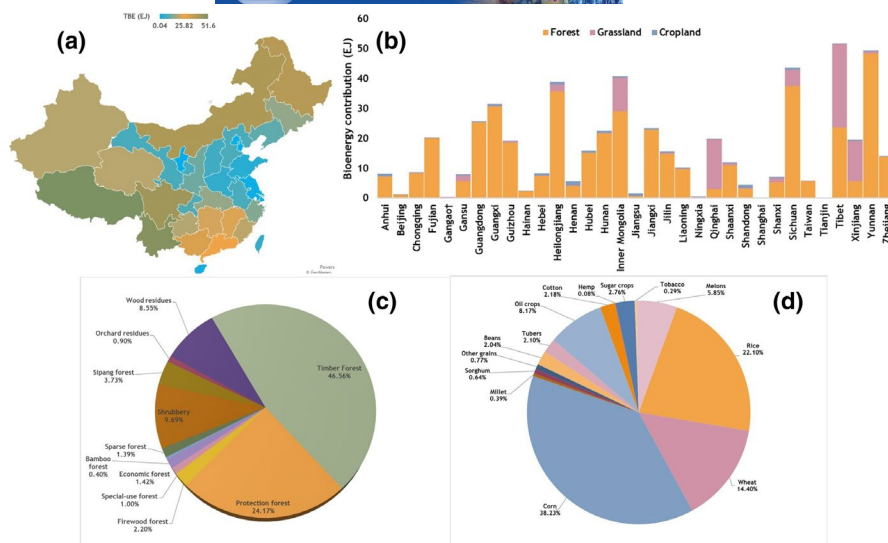
(Zhao et al., 2015). Therefore, the Chinese government should offer subsidies on conversion technologies involved in the bioethanol production process that can enhance input to product conversion ratio (Chen et al., 2016). Finally, a strong research–extension–farmer network must be established to ensure that the biomass producer or farmer can get maximum benefit. In order to gain maximum benefits from improved technologies, there is a dire need for capacity building of the extension staff. Therefore, for effective promotion of non-food-based biofuel from marginal land, future policies for the Chinese government must focus on effective marginal land utilization, feedstock improvement, and planting and conversion technologies improvement (Ge & Lei, 2017).

### 3 | STATUS OF BIOFUEL PRODUCTION IN CHINA

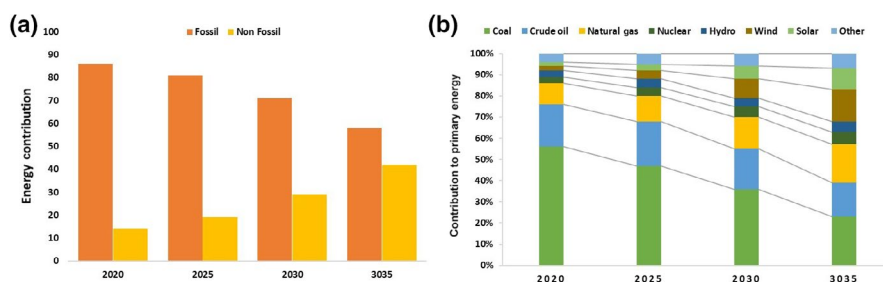
Renewable energy has a significant contribution in China's plan for low carbon economic development. During the past 20 years, China has significantly increased its renewable energy development potential and reduced the cost of renewable energy production. As a result, China has incorporated 14.3% share of renewable energy to its primary energy consumption that is very close to the 15% share which was planned during the 13th 5 year plan. In the next 5 year plan, China aimed for 20% share of renewable energy towards total primary energy consumption (EPPEI, 2019). In 2019, biofuel production in China was 111.3 PJ, which is 6.6% higher than 104.4 PJ production in 2018, while biofuel consumption in 2019 was 110.8 PJ, which is 10.4% lower than 99.3PJ in 2018 (BP, 2020). Fuel ethanol production in 2019 jumped to a record 3.4 million tons up 1.1 million tons, due to new production facilities that began operations in 2018 and



**FIGURE 3** Incentive and subsidies offered by the Chinese government to promote bioenergy and non-grain feed stock



**FIGURE 4** Bioenergy production in China. (a) Production in different provinces; (b) contribution of vegetation types to bioenergy; (c) contribution of crop residues to bioenergy; (d) contribution of forest residues to bioenergy



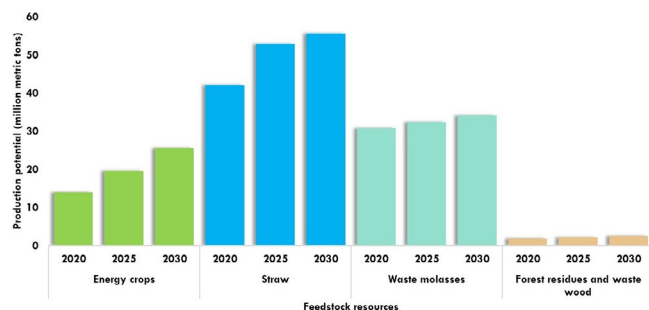
**FIGURE 5** China plan to reduce reliance on fossil fuel: (a) China plan to reduce fossil-based energy in 14th, 15th, and 16th 5 year plan. (b) Targeted share of each energy category to total energy mix during next three 5 year plans

2019. Currently, Tibet, Yunnan, Sichuan and Inner Mongolia are major contributors to China's bioenergy accounting for 9.65%, 9.24%, 8.15% and 7.63%, respectively, while Tianjin and Shanghai accounted for 0.02% and 0.01% of total biomass energy (Figure 4a). Forest biomass is the largest contributor to this biomass energy and shares 82% to total biomass energy followed by grassland which accounts for 16% of biomass energy while crop land accounts for 2% of total bioenergy. Forest land in Yunnan province contributes the maximum, which is about 11% to total forest base biomass energy while grasslands from Tibet (33%), Qinghai (22%) and Xinjiang (16%) show maximum contribution to biomass energy. Crop land from Henan and Shandong provinces has maximum contribution to current bioenergy (Figure 4b). Recent estimates show that rice, wheat and maize residues contribute maximum to biomass energy compared to other crops while timber and shrubby forest residues contribute maximum to biomass energy (Figure 4c,d).

Incorporation of 20% bio-based energy to total primary energy consumption by 2030 as planned by the Chinese government requires an additional 800–1000 GW renewable energy, which is equal to the current size of the entire electricity grid of the United States. Recently, China has released its 14th 5 year plan (2021–2025) with ambitious but realistic end-targets for renewable energy. During the 14th 5 year plan, the Chinese government aims to achieve 19%

non-fossil energy to total energy content, reduction of energy intensity by 21% and reduction of CO<sub>2</sub> emissions by 27%. Currently, fossil energy accounts for almost 86% of the total energy mix while renewable energy accounts for 14% of the total energy mix. The Chinese government plans to reduce fossil fuel-based energy to 58% and promote biofuel energy to 42% by 2020 (CNREC, 2019) (Figure 5a, b). The 3 year pollution control plan released by the State Council in 2018 emphasizes the reduction of air pollutants particularly in the Beijing–Tianjin–Hebei region, the Yangtze River Delta region and the Fenwei Plain region, in terms of reduction in PM<sub>2.5</sub> content and the number of days of heavy pollution and air quality improvement. An important development during this plan was the incorporation of Shaanxi and Shanxi as targeted regions (State Council, 2018).

Biomass resources have been exploited extensively in China for electricity and biofuel generation, and the main sources of biomass include crop residues, forest residues with production potential of 300 each and municipal waste with production potential of 210 million tons. A total of 60% of current municipal waste produced in China has potential to produce about 1–2 billion cubic meter of methane if used in landfill methane applications (Kang et al., 2020; NBS, 2019; Zhang et al., 2010). Furthermore, increasing trends in forestry and forest product industries could increase forest and wood residues with a potential of 12,000 PJ per annum by 2020

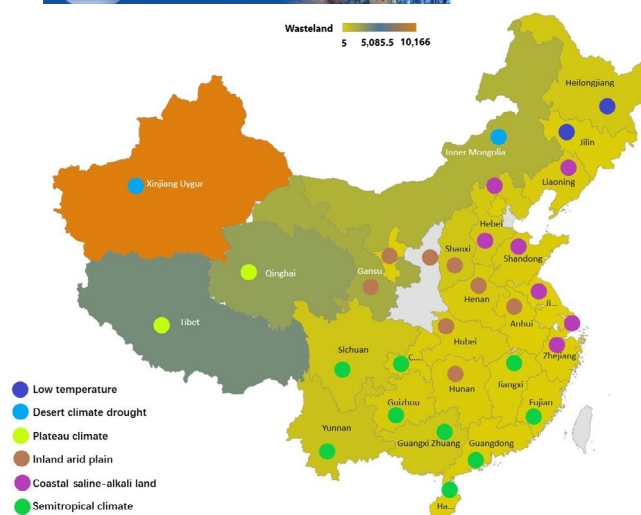


**FIGURE 6** Predicted potential of various biomass resources of China till 2030

(Drysdale et al., 2008). China is also diversifying its cellulosic biofuel feedstock by incorporating new improved bioenergy crops such as cassava and sweet sorghum for ethanol fuel production. In addition to conventional bioenergy crops, China is also promoting other plants that have bioenergy potential including *Xanthoceras sorbifolia*, *Pistacia chinensis*, *Koeleria paniculate*, *Sapium sebiferum*, *Swida wilsoniana*, *Idesia polycarpa*, *Rhus chinensis*, *Euphorbia tirucalli* and *Vernicia fordii*. Biodiesel potential of these oilseed-bearing forest trees ranges between 20.5 and 123.1 billion litres (Chang et al., 2012; Dyka et al., 2016; Li et al., 2014). In addition to trees, some second-generation energy crops can produce high amounts of biomass and have great potential for biofuel development. For example, a China native C4 perennial grass *Miscanthus* can grow in all climatic zones of China and produce high amounts of biomass. It can serve as the most prominent domesticated and well-adapted second-generation energy crop species of China. The government is planning to produce one billion tons of *Miscanthus* biomass from approximately 100 Mha of marginal and degraded land located in Northern and Northwestern China (Sang & Zhu, 2011). Increasing different feedstock resources like energy crops and forest residues can make a significant contribution to biomass energy in China. A recent study predicted that improving bioenergy potential of various energy feedstocks can enhance ethanol production by 85.18% and biodiesel production by 186.62% by 2030 (Chen et al., 2016; Figure 6).

#### 4 | MARGINAL LAND STATUS AND POTENTIAL IN CHINA

Although land resources are very limited in China, a large proportion of its total land area is wasteland. This wasteland has great potential for bioenergy after effective management and reclamation. Wasteland is not suitable for production of food crops owing to occurrence of adverse soil and environmental conditions and has potential to be used as an area for no grain feedstock growth (Li et al., 2010; Figure 7). Thus, planting bioenergy feedstock on this type of wasteland is an



**FIGURE 7** Province wise distribution of waste lands with bioenergy potential in China along with climatic conditions (Unit: area in  $10^4 \text{ km}^2$ ) adapted from Li et al. (2010)

effective and attractive approach in China and is gaining a lot of attention from the government and law makers.

Marginal lands are lands with poor soil where the environmental conditions are not suited for food crop production but are desirable for production and cultivation of plants with specialized characteristics such as halophytes and woody crops, which can serve as a source of biomass energy development. However, due to huge differences in marginal land selection, accurate definition, identification criteria and data sources from a number of studies from China are needed from different lands as marginal with different feedstock and energy potentials. Furthermore, the total marginal land area also varies due to all these factors (Cai et al., 2011; Jiang et al., 2014; Kou et al., 2008; Tang et al., 2010; Xie et al., 2015; Yan et al., 2008; Zhang, et al., 2012; Zhuang et al., 2011). A recent study divided total marginal land into three main categories, which were abandoned agricultural land, low productivity and rest land. The abandoned agricultural land accounted for 0.088%–0.404% of total land area of the country and was concentrated in Southwest and Southeast China. The low-productive land accounted for about 5% of total land area and included the western regions such as Tibet and part of Qinghai province. About 12% of total land area fell under the rest of land category and was distributed throughout China with shrub cover, herbaceous cover and sparse herbaceous cover land as the main vegetation types (Li et al., 2017). According to another estimation, 61.1 Mha of marginal land suitable for biomass energy production was identified (Guo & Hanaki, 2010; Wang & Li, 2011). A survey conducted by the Ministry of Agriculture in 2008 investigating marginal land resources of China that have potential for energy crop cultivation identified about 34 Mha<sup>2</sup> land area consisting of 7 Mha<sup>2</sup> winter fallowed paddy land and 27 million hm<sup>2</sup>

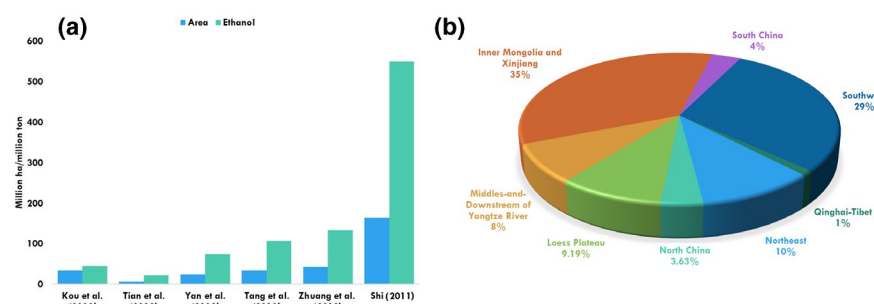


of wasteland marginal land suitable for bioenergy crop cultivation (Kou et al., 2008). Another study estimated 82.3 million  $\text{hm}^2$  marginal land area was suitable for biomass production out of which 24 million  $\text{hm}^2$  could be reclaimable (Yan et al., 2008) and about 7 million  $\text{hm}^2$  was suitable for bioenergy crops cultivation (Liao & Zhang, 2000; Xu et al., 1998; Yang et al., 1999). Concluding results from multiple studies demonstrate that about 24–163.74 Mha land area in China is marginal and such a huge difference in the data range reveals a high degree of variability in estimation methods and different criteria used to define marginality of land by various researchers. Approximately 16.825%–17.6% of total land area is suitable for bioenergy crop production and cultivation in China (Li et al., 2017). Mainly, many types of these marginal lands are concentrated in the southwest and northwest of China as well as the northeast of Inner Mongolia (Figure 8a,b).

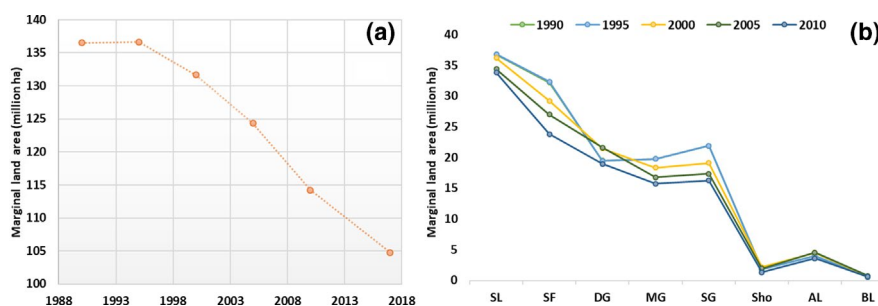
A study in 2015 estimated that marginal lands suitable for bioenergy crops are being squeezed in the past 20 years in China due to human activities and natural factors (Figure 9a,b). They proposed that marginal land suitable for energy plants will continue to decrease in the future and land variation factors should be considered in the evaluation of biomass energy resources and industrial layouts (Jiang et al., 2014; Zhang, 2010).

As marginal lands differ in their area and climatic conditions, they differ considerably in their bioenergy potential. A recent study estimated that total annual geographical potential

of energy plants planted on marginal lands was 17.816–19.373 EJ (Li et al., 2017), slightly higher than the previous estimate of 16.107 EJ annually (Shi, 2011). This study estimated that by using conventional and bioenergy crops as feedstock, 290  $\text{Mt year}^{-1}$  of ethanol can be produced from marginal land while growing energy crops on different types of marginal lands including wasteland, land riser/boundary, mining land and roadside land, China can produce 150 Mt of ethanol (Tang et al., 2010). Similarly, two cellulosic crops switchgrass and *Miscanthus* on 47 M ha marginal land in China could produce 70–110 Mt ethanol annually. Furthermore, switchgrass could yield 70–110 Mt ethanol while *Miscanthus* can yield 230–330 Mt ethanol largely depending on conversion technologies (Qin et al., 2011). One study predicted that China can produce 152.13 million metric tons of non-food biofuels by 2030 from multiple resources including planting energy crops on marginal lands (Chen et al., 2016). Based on resource availability, another study concluded that growing energy plants on marginal land could produce 8,905 PJ/year in 2030 (Zhao, 2018). Similarly, production potential of each bioenergy crops on marginal land differs partly due to different environmental and soil conditions. A study reported cassava yield on marginal land in China was 52.51 million tonnes and the energy ratio value varied from 0.07 to 1.44, whereas the net energy surplus of cassava-based fuel ethanol in China was 92,920.58 million MJ (Jiang et al., 2019). The production potential of *Xanthoceras sorbifolia* and *Cerasus humilis* from



**FIGURE 8** Marginal lands in China: (a) total area and bioenergy production potential of marginal lands estimated in different studies from China, (b) occurrence of marginal lands in different regions of China



**FIGURE 9** (a) Reduction in marginal land area suitable for bioenergy feedstock and (b) contribution of different marginal land type to total marginal area in China; SL: Shrub land, SF: Sparse forest land, DG: Dense grassland, MG: Moderate dense grassland, SG: Sparse grassland, Sho: Shoal/bottom, AL: Alkaline land, BL: Bare land



marginal lands located in North China, *Jatropha curcas* and *Cornus wilsoniana* in the southwest and southeast China and *Pistacia chinensis* grown in central China, while also having a northeast–southwest zonal distribution was  $32.63 \times 106$  t/yr when considering the overlapping areas. While potential productivity without considering the overlapping areas was  $6.81 \times 106$  t/yr from *X. sorbifolia*,  $8.86 \times 106$  t/year from *C. humilis*,  $7.18 \times 106$  t/year from *J. curcas*,  $9.55 \times 106$  t/year from *P. chinensis* and  $7.78 \times 106$  t/year from *C. wilsoniana*. Sorghum varieties grown on marginal lands with low temperature conditions in Inner Mongolia have almost constant biomass yield from different parts and higher total content of hexose and pentose in stems (725.4 g/kg) than leaves (642.3 g/kg) (Diallo et al., 2019). According to an estimation, biodiesel potential from energy crops grown on marginal lands in different regions of China will reach 25.57 million metric tonnes with maximum contribution (1,165.73 ten thousand metric tons) from *Xanthoceras sorbifolium* (Chen et al., 2016).

## 5 | CAUSES OF LAND MARGINALITY IN CHINA

Various regions or cities of China are very vulnerable and at high risk of climate change. Water resources of the country are very limited as a study from 2013 demonstrates availability of only 6% of freshwater resources to feed 21% of the world's population. (Wong, 2013). In addition to high drought stress, overgrazing, deforestation, mining and land conversion have left many regions of the country highly vulnerable. China is developing strategies of land restoration to cope with frequent floods, desertification and sandstorms in the region near Gobi particularly when considering increased threats from climate change and the need for food and natural resource security (WorldBank, 2006). Major causes of land degradation and/or marginality and their occurrence among various region of China are reviewed below.

### 5.1 | Salinization

Saline soil contains a high enough concentration of soluble salts to influence plant growth (Li, et al., 2016). According to Zhaoyong et al. (2014), the area of salinized soil in China is about 36.93 million ha, which accounts for about one-third of the total arable land. In the oasis basin of Xinjiang in north-west China, the area of salinized soil makes up about 1.05 million ha, which accounts for 33.4% of the total agricultural land in the region, and research has found that the salinity of this area is trending upwards reviewed in Claudio (2018) and Zhaoyong et al. (2014). According to Yang (2006), climate change is another significant driving factor in the salinization of the soil. North and north-east China are becoming warmer

and drier, which contributes to the increasing salinization of the region's soils. Wind and air, waterlogging, water used for irrigation and impeded drainage in areas irrigated by continuous flooding are the main reason for land salinization in China reviewed in Claudio (2018)

### 5.2 | Acidification

One study collected all published data on topsoil pH from 2000 to 2008 and the results showed considerable acidification of all top soils, especially soils cultivated with cereal or cash crop that received high fertilizer inputs, with an average pH decline of 0.13–0.8 (J. H. Gao et al., 2018). In some areas, the pH values dropped by 0.8 over two decades, with some soils growing high-input cash crops reaching a pH of 5.07. As a comparison, when soil is left under natural conditions, it takes at least 100 years to reach this level of acidification (Gilbert, 2010). Another study in Foshan (Guangdong Province) showed that 90% of the soil samples in the study area had a pH < 4.5, and only 8% of soils had a pH within the range 4.5–5.5 in the year 2008 and 2009 (Hou et al., 2012).

### 5.3 | Desertification

China now has 261 million ha of soil that is classified as undergoing desertification. This corresponds to about 27.2% of the China mainland, and is spread across 528 counties in 18 provinces, autonomous regions and municipalities, directly affecting some 400 million people (Hao, 2016). Desertification is mostly observed in the provincial regions of Xinjiang, Inner Mongolia, Tibet, Gansu, and Qinghai, which together account for 95.48% of the total area of desertified lands in China (SFA, 2011).

### 5.4 | Sandification

Up to 2014, the total sandification area in China was 172,117,500 ha, which accounts for 17.93% of the total land area and reduces by 990,200 ha. The sandified land in China is distributed in 30 provinces, 920 counties and 8,146 townships. It is the most severe in Xinjiang, Inner Mongolia, Tibet, Qinghai and Gansu where the sandification area count was 43.40%, 23.70%, 12.54%, 7.24% and 7.07% of the total sandification area in China respectively (UNCCD, 2017).

### 5.5 | Soil and water erosion

The area of soil and water loss (water erosion) in China in 2011 was 1,293,200 km<sup>2</sup>. The area of mild, moderate, intense,

extremely intense and violent is 667,600, 351,400, 168,700, 76,300 and 29,200 km<sup>2</sup>, respectively, counting for 51.62%, 27.18%, 13.04%, 5.90% and 2.26% respectively. Most serious soil and water erosion in China takes place in the Loess Plateau of mid-reach of Yellow River and southwestern karst area (UNCCD, 2017).

## 5.6 | Mining

An estimation by the Ministry of Environmental Protection (MEP), China, revealed the extent of soil degradation in the mainland, showing that about one-fifth of uncultivated land in China is contaminated with heavy metals (MEP, 2014; Patel, 2014). Mining is the main factor responsible for land contamination as China hosts about 9,000 large- and medium-sized mines and 26,000 small mines (Li et al., 2014). Mining activities result in accumulation of heavy metals in surrounding lands that not only affect atmosphere quality but also impose serious health risks to the population living in nearby areas (Hu et al., 2010). Several mines are located in the Loess Plateau area where they are causing major problems to the soil, environment and public health. Open-cast coalmines are primarily located in the environmentally vulnerable regions of northwestern China, such as Gansu, Shanxi, Ningxia, Inner Mongolia and Shaanxi provinces of China (Zhang et al., 2016).

## 5.7 | Forest and grassland loss

China is the main processing hub of forest and forest residues since 2000, since China is now the largest consumer and importer of wood and forest-based products (Hoare, 2015). Due to rapid forest and tree loss, China was ranked one of most forest deficient countries in the world with forest cover 9% less than the global forest average of 31% (FAO, 2012). Many factors including overgrazing, urbanization, agriculture, mining, high CO<sub>2</sub> and nitrogen deposition are responsible for grassland degradation (Veldman et al., 2015). Grasslands in China are either degraded or have very low productivity, and these types of grasslands are present in the western and northern provinces such as Tibet, Qinghai, Xinjiang, Gansu and Inner Mongolia (Chen & Fischer, 1998).

## 6 | PLANT IMPROVEMENT FOR BIOENERGY PRODUCTION ON MARGINAL LAND

Adverse environmental conditions such as biotic or abiotic stress and soil conditions in marginal land hinder the yield and biomass production of various energy crops that grow on marginal land. Thus, for effective utilization of marginal

lands in addition to land management practices, plant improvement is required to tolerate adverse conditions and produce high biomass (Jones et al., 2015). A bioenergy plant is ideal for cultivation on marginal land if it has the following characteristics, perennial life cycle with C4 photosynthesis, long canopy duration, fast growth during spring, high water and light use efficiency and ability to store nutrients in its roots which can be used during adverse conditions (Sticklen, 2008). Thus, breeding for many traits like light interception, photosynthesis, plant architecture and carbon partitioning efficiency could significantly enhance crop biomass production in marginal lands. Herbaceous plants with dense canopies and large leaf area and number yield higher biomass due to deep penetration and interception of light (Boe & Beck, 2008; Fernandez et al., 2009; Song et al., 2013). In woody species, vertical growth habit and production of sylleptic branches are also important to attain high plant densities and increase biomass yield per hectare (Dubouzet et al., 2013; Marron et al., 2006; Rae et al., 2004). Two important determinants of efficient biomass synthesizing plants are carbon partitioning efficiency and efficient root system establishment to store high amounts of carbon reserves (Jones et al., 2015; Zhu et al., 2010). Change in the expression patterns of sucrose synthase genes or sucrose transporters in plants using genetic engineering can also enhance biomass production (Braun et al., 2014; Yadav et al., 2015). A study on switchgrass showed that overexpression of Sucrose Synthase (PvSUS1) can lead to increased plant height (37%), biomass yield (13.6%) and tiller number (79%). The role of roots in biomass production is less studied because it is costly, time-consuming and technically demanding, especially in field conditions (Pierret et al., 2016). Two important factors determining plant biomass are the duration of exposure, which determines the capacity of plants to capture light, and the stage of plant growth, which determines the ability of plants to synthesize maximum biomass in vegetative tissues before maturity (Jones et al., 2015; Salas Fernandez et al., 2009). An ideal bioenergy plant for marginal land must have a long growing season, as well as a developed and dense canopy with lack of or very reduced reproductive structures (Jones et al., 2015). C4 plants show high sunlight to biomass conversion ability compared to C3 plants due to their ability to prevent photorespiration by sustaining high CO<sub>2</sub> concentrations (Mann et al., 2013). Thus, C4 plants are preferred for planting in marginal lands (Schuler et al., 2016; Zhu et al., 2010).

One common approach is to search and screen bioenergy crops for induced or natural variations to enhance biomass and/or saccharification efficiency of biomass. Generation of chemically and biologically mutated rice with higher biomass and saccharification efficiency has opened up new avenues for bioenergy research to use nonedible organs for bioethanol production (Li et al., 2015). A set of chemically generated

mutants of *Brachypodium distachyon* showed 20%–60% higher saccharification efficiency than their wild-type counterparts providing materials for further experiments aimed to discover new biochemical routes for industry (Marriott et al., 2014). A mutant population of *Arabidopsis* with defective starch-degrading enzymes, modified auxin transport and other mechanisms was generated with increased saccharification efficiency (Stamatiou et al., 2013).

Bioenergy crops produce large amount of lignocellulosic biomass which not only differ in quantity but also in quality. Different types of biopolymers and biochemicals are reported from lignocellulosic biomass of different species, but its extraction and processing are difficult and expensive (Isikgor & Becer, 2015; Trindade et al., 2010). Lignocellulosic biomass is degraded into different polymers that by the action of various enzymes or treatments are converted into biofuel. Physical and chemical pretreatments coupled with enzymatic digestion and yeast-mediated fermentation of soluble sugars are basic steps in the conversion of plant biomass into ethanol or biofuel (Carroll & Somerville, 2009; Xu et al., 2012). Plant cell walls, an abundant renewable biomass resource for biofuels on earth, contribute lignocellulosic biomass in a major way (Hao & Loqué, 2017; Isikgor & Becer, 2015). Complexity in structure, mechanical strength and polysaccharide composition has made physical and biochemical digestion of the cell wall difficult in nature and recalcitrance of lignocellulosic biomass has an unacceptably high cost (Felby, 2009; Loqué et al., 2015). The cell walls of foodstocks are easily destructible and thus require milder and cheaper treatments to be used as biofuel or other bio-based products compared to other plants. Increasing content of a specific molecule or identifying biopolymers that interfere with digestibility of lignocellulose biomass in bioenergy plant cell walls by using plant breeding and biotechnology approaches could enhance biomass end use for biofuel production (Haghighi Mood et al., 2013; Xie & Peng, 2011). However, identification of one wall polymer is technically difficult as alteration in expression of one gene in mutants could change multiple wall polymers. Systems biology-based analyses of large biomass yielding plant populations have identified three main wall components involved in cell wall synthesis that are cellulose, hemicellulose and lignin (Wang et al., 2016).

Prior knowledge of the chemical constituents of biomass is vital as it may affect the final product composition and energy conversion process. Lignocellulosic biomass with low lignin content can efficiently be converted into ethanol (Weng et al., 2008) due to recalcitrant effects of lignin on biomass conversion (Rocateli et al., 2012). Likewise, high ash content in biomass also hinders thermochemical conversion efficiency of biomass (Cassida et al., 2005). Thus, understanding factors affecting biomass conversion such as enzyme inhibition, cellulose accessibility, and enzyme adsorption are

vital for bioenergy production. As these factors reduce bio-conversion efficiency of enzymes, they also provide many opportunities for end-product yield improvement through feedstock genetics coupled with process engineering (Feltus & Vandenbrink, 2012).

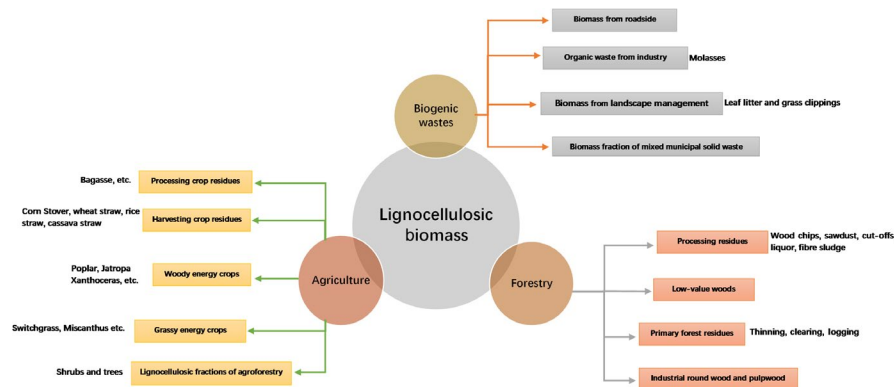
## 7 | BIOMASS RESOURCES OF CHINA

### 7.1 | Food crops

Corn grain ethanol is one of the most important first-generation biofuels. Its lifecycle GHG emissions are higher than cellulosic ethanol due to its potential land use change impacts (Dunn et al., 2013; Qin et al., 2016). Yet in many countries, including China, corn ethanol has been limited to avoid competition with food production. Corn grain ethanol currently accounts for 82% of China's first-generation petrol, while Cassava 's dried chip and wheat kernel accounts for 13% and 5% of food crop biofuels (USDA, 2019). In 2007, the government banned the use of grain for the potential expansion of biofuel production due to increasing concerns about the effects of biofuel expansion on food security. The use of these feedstocks in the light of competing uses, especially livestock feed, must be considered carefully. Increasing the use of bioenergy to substitute fossil fuels will minimize air pollution such as sulphur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) (Fan et al., 2007).

### 7.2 | Agricultural residues

Straw and stalks from various food crops such as rice and wheat produced as by-products during cultivation and harvesting practices are the main components of agricultural straw (Zhao, 2018; Figure 10). China has made excellent progress in grain and straw production over the last three decades and an estimate shows that crop residues will reach 545 million tons in 2020 (Wang et al., 2010). As crop residues are by-products of crop cultivation, production and collection, and utilization of straw does not compete with crop land resources and serves as an effective resource of renewable energy generation. As China is among the top ranked rice and corn producers, it can produce large amounts of crop residues annually. Proper utilization of crop residues in the future could make a significant contribution on reducing fossil-based reliance of the country. Crop residue production and its energy potential is investigated by many researchers both at the province level (Liu et al., 2012; Sun et al., 2013; Zhang et al., 2019) as well as nationwide (Catania, 1999; Xiaoguang Chen, 2016; Jiang et al., 2012; Liu et al., 2008; Qiu et al., 2014; Zeng et al., 2007). China produces about



**FIGURE 10** Biomass resources of China

600–800 million tons of crop residues annually; however, for regional bioenergy development, a deep assessment of types of crop residues and production potential is required (Gan & Yu, 2008). Furthermore, some parts of crop residues are burned in fields by farmers whereas some portion of total crop residues are kept as leftovers to improve soil fertility and prevent erosion (Bi et al., 2008; Jiang et al., 2012; Shi, 2008).

### 7.3 | Energy crops

Cellulosic bioenergy crops in addition to bioenergy production can also minimize the environmental costs (Qin et al., 2011; SANG & ZHU, 2011; Figure 10). Many regions of China have started planting cassava and sweet sorghum as sources of cellulosic biomass recently (USDA, 2015). Cassava has accounted for around 35% of China's total bioethanol production capacity (Baeyens et al., 2015). Due to the limited areas in China, cassava cultivation is concentrated in Guangxi, Guangdong, Hainan, Yunnan, Fujian and Jiangxi provinces. The six provinces yield about 97% of total cassava output with maximum contribution (about 60%) from Guangxi Province (Fu et al., 2018; Ming-yu, 2008). The Ministry of Agriculture increased cassava planting area to 1 million hectares in 2015 and established the world's first large-scale cassava ethanol producing plant in Guangxi by China National Cereals, Oils and Foodstuffs Corporation (COFCO) with annual production capacity of 200,000 metric tons (Nesbitt et al., 2011). From 2010 to 2019, cassava-based bioethanol production increased from 1,009 thousand million litres to 1,424 thousand million litres while cellulosic biomass-based bioethanol production increased from 240 to 450 thousand million litres during 2012–2016 (USDA, 2019).

China is a major centre of sorghum diversity and mainly cultivated in the northern and northeastern regions of the country. Various breeding approaches are employed in China to develop a vast diversity of sorghum, and these hybrid varieties exhibit higher biomass production than their parents (Burow et al., 2012; Mathur et al., 2017; Zhang, et al., 2010). In northern China, sorghum showed high energy efficiency

coupled with high economic returns at saline-alkali land (Liu et al., 2015; Ren et al., 2012). A study revealed that ethanol production from Sorghum can be increased to  $244.0 \times 10^4$  t/year if whole grain sorghum is replaced by sweet sorghum. Addition of this amount of ethanol to the overall system will satisfy 63.2%–84.9% of the country's current demand of E10 (Zhang, et al., 2010). A recent study estimated that the suitability of marginal lands from different regions of China for sweet sorghum plantation. Results revealed that biofuel potential of sweet sorghum in high-slope farmland (0.30–0.73 EJ) and marginal land (11.98–15.18 EJ) can satisfy the biofuel goal in 2050 (6.70–8.60 EJ). Heilongjiang, Jilin, Inner Mongolia and Liaoning, Hebei, Shanxi, Sichuan, Xinjiang and Yunnan are the most suitable provinces for sweet sorghum production (Nie et al., 2019).

South China hosts the most sugarcane production which is increasing. Over the last few decades, the highest expansion in sugarcane production has been seen in Guangxi and Yunnan Province while in Guangdong, it is decreasing due to the development of non-agricultural industries having higher potential than sugarcane (Peng et al., 2014). Many commercial sugarcane varieties developed in China differ in their sucrose content or cane yield or both and these include Funong95-1702, Yuetang93-159, Yuetang94-128 and Guitang94-116. For example, sucrose content of Yuetang93-159 increased up to 31.86% and cane yield was 26.6% higher than major commercially grown ROC10 cultivar when planted under the same environmental conditions (Guishui, 2009).

The latitudinal range between  $\sim 25^{\circ}\text{N}$  and  $\sim 110^{\circ}\text{E}$  in China is considered a diversity hotspot for *Miscanthus* and distribution of species varies with latitude, for example, *M. lutarioriparius* grows at  $30^{\circ}\text{N}$  while *M. sacchariflorus* grows between 30 and  $45^{\circ}\text{N}$  (Sun et al., 2010). Liaoning Jilin and Hainan, Guangxi, Guangdong, Yunnan provinces are habitat of *M. sinensis* while *M. floridulus* grows in Anhui and Hubei and *M. sacchariflorus* is concentrated in northern Jiangxi and Hunan provinces (Sacks et al., 2013). Furthermore, marginal lands distributed in central part of Northeast China and the Loess Plateau are priority zones for cultivation of *Miscanthus*



as a bioenergy crop. A study found that there was about 27.6 Mha of marginal land suitable for energy production with a total annual production of 0.41 billion tons of biomass in the Loess Plateau of China. Furthermore, soil carbon sequestration was 9.3 Mt C year<sup>-1</sup> and they predict that it will take only 0.97 years on average to repay the carbon debt (Liu et al., 2016).

Switchgrass is a perennial C4 plant with efficient photosynthetic pathways (Lewandowski et al., 2003) and has advantages over annual crops to produce cellulosic biomass because it does not require annual establishment. This property not only provides the necessary economic and net energy inputs (Mitchell et al., 2008) but also reduces the risk of soil erosion (Ma et al., 2000). Nineteen different switchgrass cultivars/lines were tested in the Loess Plateau located in Northcentral China with altitudinal range between 34° and 41°16'N and 101°–114°33'E with yield potential from 9.5 to 5.6 Mha reviewed in Cooney et al. (2017). A recent study demonstrates that total of 284 dry weight Mt/year of switchgrass could be obtained from 30 Mha marginal land with technical potential of 5.1 EJ/year (Zhang et al., 2020).

Jerusalem artichoke (*Helianthus tuberosus*) is a member of the sunflower family native to North America and is well adapted to marginal lands specifically to salt effected and drought prone lands. Thus, it is selected as a cover crop for large-scale cultivation in saline–alkaline soils or coastal shoals (Long et al., 2010; Rossini et al., 2019). Due to its strong adaptability, Jerusalem artichoke is widely distributed in China as a cultivated crop (Taha et al., 2012). Its ethanol yield ranges from a minimum of 1,500 l/ha to a maximum of 11,000 l/ha (Lachman, 2008). The average net calorific value of dry biomass harvested in autumn could be up to 18.0 MJ m<sup>2</sup>, compared to the spring figure of 18.5 MJ m<sup>2</sup> (Rutkauskas, 2005). The net calorific value can also be expressed as 14.6 kJ g (Long et al., 2016; Vacek, 2013). It is well suited for marginal lands in arid or semi-arid conditions in China and usually preferred to be cultivated on Loess Plateau in China along with Hebei, Henan, Anhui, Shanxi provinces. *Jerusalem artichoke* has high tolerance to drought, diseases and insect pests, and can survive between –40 and –30°C. In the west region of Heilongjiang Province, Jerusalem artichoke can have a tuber yield of 30–45 t/hm<sup>-2</sup>, even up to 75–150 t/hm<sup>-2</sup> (Long et al., 2016; Shi, 2010). *Erianthus arundinaceus* (Sweetcane) is a tall, perennial crop that prefers to grow in hot climates and is native to southern China. It is considered an important genetic source for the sugarcane breeding programme. The species is related to taxa in *Miscanthus*, *Narenga*, *Saccharum* and *Sclerostachya*, so it is considered a member of the ‘sugarcane complex’ (Amalraj & Balasundaram, 2006; Wang et al., 2019). All sweetcanes were found in the tropical and subtropical areas of China,

specifically in the regions east of the Tibetan Plateau, south of Huai River–Qinling Mountains line. Sweetcane was generally found below an altitude of 1,500 m; however, it could be distributed up to 2,350 m (Yan et al., 2009). Sweetcane had a relatively high biomass yield when compared with other bioenergy plants grown in the same environment (Singh et al., 2015; Zeng, 2013). The high yield of sweetcane corresponded to growth conditions, planting time and harvest time (Palmer et al., 2014; Singh et al., 2015; Yan et al., 2014). For instance, sweetcane biomass yield in test field reached to 43.76 t/ha in Huaihua, Hubei, while it gave 38 t/ha when tested at Changsha, Hunan. When tested at Nanning, Guangxi, the biomass yield was 11.27–25.16 t/ha while in constructed wetland, it produced 9.5 t/ha biomass (Hou et al., 2015; Wang et al., 2019; Yao et al., 2016; Zeng et al., 2013). A study on 20 sweetcane varieties cultivated in Sichuan Province showed that coefficient of dry matter production per plant was 25% (Liang, 2011).

## 7.4 | Forest resources

Forest tree biomass energy is a kind of energy stored in the forest. It has the characteristics of less pollution, low ash content and is renewable, and the forest tree can effectively absorb carbon dioxide in the atmosphere during the growth process. Therefore, the forest tree biomass energy reduces greenhouse gases and plays an important role in plateauing. China is very rich in forest resources, with forest area of 207,690,000 HM<sup>2</sup>, and total standing stock volume of 16.433 billion m<sup>3</sup> (SFB, 2019). Abundant forest resources have laid a good foundation for the development and utilization of forest biomass energy in China. Many researchers have analysed and evaluated the status of forest biomass energy resources, mainly focusing on the evaluation of the potential of forest biomass energy resources in micro-regions, and the evaluation of the potential of specific types of forest biomass energy resources (Fu et al., 2020; Qu et al., 2016; Xie et al., 2018; Yang et al., 2013; Zhang et al., 2015). A study in 2015 estimated potential of different types of forest residues from China. Total potential of these residues was 169 million tons with maximum contribution (38%) of wood felling and bucking residues followed by wood processing residue which accounted for 37% of total residue potential. East China shares maximum (39%) to these forest residues followed by Southwest (17.4%) and South China regions (16.3%) while Shandong displays the highest contribution to biomass potential accounting for about 11.9% of total resources (Zhang et al., 2015).

Forest-based bioenergy development is favoured because it does not compete with agricultural crops for land resources and thus avoid food versus fuel competition. According to strategy of the Chinese government, all new forests will be

established on marginal land not suitable for food crop cultivation. Approximately 54 million ha area of the country comprising of barren and waste land is suitable for plantation of bioenergy forests (Peidong et al., 2009; Zhuang et al., 2010). In addition to small-scale energy plants including shrubs, trees can be planted on marginal lands. A survey by SFA in 2011 reported that 12 Mha land suitable for bioenergy tree plantation is available and distributed across 21 provinces of China (Schweers et al., 2011; Yang et al., 2013; Zhuang et al., 2011).

Trees with bioenergy potential show high diversity and about 30 woody plant species with about 40% oil content in their biomass have been reported in literature. Major advantage of these oil-bearing plants is they have a long harvest period and are well adapted to diverse and harsh climatic conditions so they have great potential for plantation at marginal lands (Shao & Chu, 2008). *Metroxylon sagu*, *Manihot esculenta*, *Jatropha curcas*, *Sindora glabra*, *Cornus wilsoniana*, *Euphorbia tirucalli*, *Pistacia chinensis*, *Camellia oleifera*, *Garcinia multillora*, *Simriaondsia chinensis*, *Cinnamomum pauciflorum*, *Sapium sebiferum*, *Sapindus mukorossi*, *Swida wilsoniana*, *Vernicia fordii* and *Xanthoceras sorbifolia* are some important forest plants with bioenergy potential and their composition and spatial distribution in China has been reviewed (Zhang et al., 2012). *Jatropha* is also forest-based bioenergy crop of China.

The cultivation area of *Jatropha* in China was 0.15 million ha in 2008 and 95% of cultivation area lies in Yunnan, Guizhou and Sichuan Province. The *Jatropha* seeds contain 27%–40% of oil which have the ability to produce fine quality biodiesel (Weiguang et al., 2010). The Chinese government is promoting *Jatropha* cultivation at multiscale involving a number of ministries, agencies and bureaus at the national, provincial and municipal levels. For example, development and utilization of *Jatropha* resources in Jinsha hot-dry valley region (2002–2004) and energy crop development and utilization in Southwest China (2004–2006) are two of many *Jatropha* biofuel producing projects in China (SFA, 2011; Yang et al., 2012; Yang et al., 2013). In addition to *Jatropha*, seeds from *Quercus* have high starch content (about 50%) and *Quercus* trees are planted on about 18 million ha with annual production potential of 10 Mt with theoretical ethanol yield 2.5 Mt. *Radix pueraria* contains about 30% starch content and has annual production of 1.5 Mt. (SFA, 2011; Jun Yang et al., 2013). Poplar is another important bioenergy plant that is planted in south temperate central areas of Anhui, Hubei, Henan, Jiangsu, Shandong, Shanxi and Zhejiang provinces. The area of plantation of *Populus* in these provinces is about 600,000 km<sup>2</sup> (Fang et al., 2005, 2010). Recent estimation has shown that it is planted across 825.49 thousand M ha, accounting for 10.9% of the national plantation area (SFB, 2019).

Furthermore, poplar is also used for intercropping with conventional crops like wheat, corn and soybean cropping systems. A study aimed to compare the effects of three poplar intercropping designs and two intercropping systems (wheat–corn cropping system and wheat–soybean cropping system) on biomass production and C stocks in poplar intercropping systems revealed that poplar biomass increased with increasing tree density, ranging from 8.77 to 15.12 t/ha (Fang et al., 2010).

## 7.5 | Forest residues

Woody biomass from forest resources makes a significant contribution in China's sustainable energy development. A recent estimate revealed that forests account for 22.96% of total land area with capability of about 18.802 billion tons biomass production and carbon stock of 9.186 billion tons (SFB, 2019). The annual production of forest residues was 197.2 Mt per year 2011, and in combination with fire wood and shrub residues, these can reach 300 Mt per year (Zhou et al., 2011). These residues were 257.44 Mt with annual potential of 54.69 Mt in 2016. Of total wood residues, 43.34% (98.83 Mt) was contributed by forest pruning residue, 16.39% (37.37 Mt) was contributed by wood logging residue and 18.73% (42.72 Mt) was contributed by wood bucking residue. In addition to natural forest, planted forest also made a significant contribution to the country's biomass yield, for example, planted bamboo processing residues and waste bamboo accounted for 21.26 Mt and 1.60 Mt to total forest-based biomass respectively. Three provinces namely Guangxi, Yunnan and Fujian contribute 17.88–32.66 Mt, highest among all provinces, to total forest-based residues (Fu et al., 2020). Generally, Southeast, Southwest, Northeast and Xinjiang are hotspots for production of forest-based wood biomass production, though these can be collected throughout the country (Yanli et al., 2010).

## 7.6 | Other plants with bioenergy potential

Many halophyte species were found effective for biomass and energy production, in addition to various other advantages, they can be irrigated with contaminated water without affecting biomass yield (Sharma et al., 2016). They show high biomass and grain yield in saline condition compared to other crops, for example, *Salicornia bigelovii* a halophyte can produce 18 tons of biomass per hectare and two tons per hectare of seeds when grown on saline lands (Glenn et al., 1991). Many drought tolerant species have the ability to yield high biomass in drought prone areas, for example, higher tolerance to drought, disease, insect

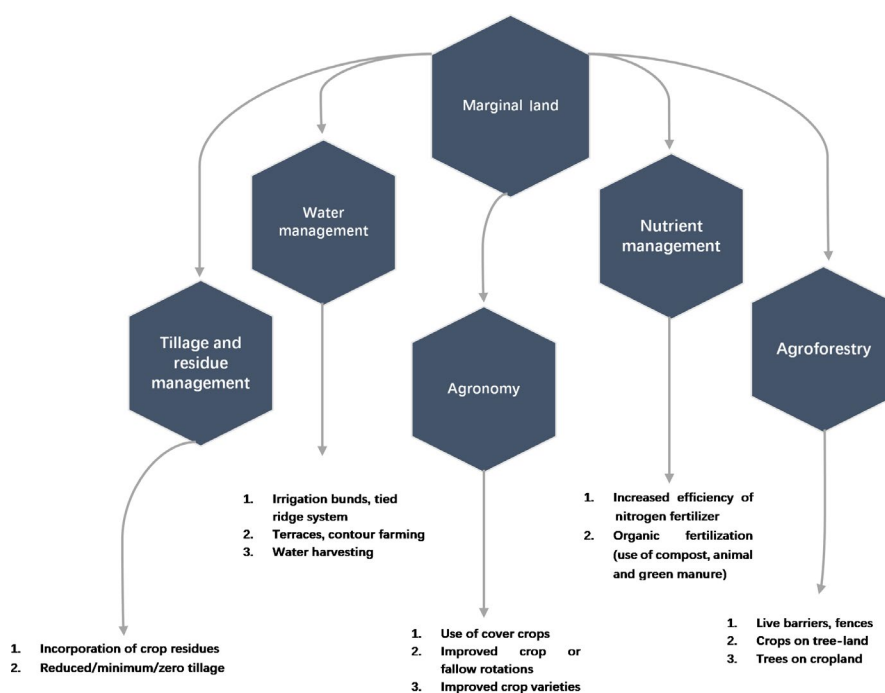
and heat stress make Jerusalem artichoke an ideal candidate as a bioenergy crop in various regions of China where it has 30–45 ton/hm<sup>-2</sup> or up to 75–150 t/hm<sup>-2</sup> tuber yield (Newton et al., 1991).

Mangroves are one special type of salt-tolerant species at the interface between land and sea in tropical intertidal forest communities. Mangroves in China are mainly distributed in the southeast coastal tropical, subtropical coastal harbours, estuary bays and other sheltered waters. North from Hainan Island, with the gradual rise of latitude, the climate belt from the central tropics (southern Hainan Island, the northern Leizhou Peninsula and the southern part of Taiwan), the South Asian tropics (Guangxi, Guangdong, Northern Taiwan and Fujian Province, the southern coastal areas of Fujian Province) (Baowe, 2014). China host 502 species of halophytes belonging to 218 genera and 71 families (Lin, 2004; Zhao, 2005; Zhao et al., 1999). *Rhizophora mucronate*, *Rhizophora stylosa*, *Pongamia pinnata*, *Cerbera manghas*, *Barringtonia racemosa*, *Vitex trifolia* Linn. var. *simplicifolia*, *Clerodendrum inerme*, *Excoecaria agallocha*, *Hibiscus tiliaceus*, *Avicennia marina*, *Nypa fruticans* and many other mangrove species have bioenergy potential (Hui-Min et al., 2012). In addition, many fibre plants, starch containing plants and algae can also serve as an effective source of forest-based bioenergy. There are many advantages in using algal biomass. It has a greater ability to produce biofuel than other grain and non-grain crops (Tan et al., 2015). A study in 2011 revealed that a hectare of algae has the ability to produce 20,000 gallons per year of biodiesel compared to 18 gallons by 1 hectare of corn and 700–800 gallons by 1 hectare of palm trees (He & Yang., 2014).

## 8 | MARGINAL LAND MANAGEMENT TO ENHANCE BIOMASS FEEDSTOCK PRODUCTION

It is usually difficult practically to convert marginal lands into biomass producing lands due to their heterogeneous nature. Multiple factors including poor soil structure, soil degradation, site abandonment or environmental contamination may be responsible for marginality so multiple factors need amendment. Furthermore, these lands differ considerably in their quality and productivity and plant requirement of these factors differs with species, so it is not possible to use the same marginal land for multiple crops (Campbell et al., 2008; Gopalakrishnan et al., 2011). Many strategies are employed by farmers and other stakeholders to improve productivity of marginal lands, including harvesting of cover crops for biofuel production (Austin et al., 2017; Qi-Qi et al., 2015), establishment of perennial biofuel crops in the edges of field filter strips (Cibin et al., 2018) (Figure 11).

Establishment of a bioenergy crop on marginal land with adverse conditions is the first and most vital step for its sustainable production. Many management practices including seed quality, plantation time, row spacing, weed management and seeding rate must be considered for effective establishment of any crop at marginal land. To conserve soil moisture content and to prevent soil erosion, a zero-tillage planting of energy crops is preferred (Douglas et al., 2009). Row spacing also has a vital role in crop establishment and biomass generation, for example, in the case of switchgrass narrow spacing could increase biomass yield per unit and



**FIGURE 11** Marginal land management strategies

improve water use efficiency compared to widely planted (Gao et al., 2015). Furthermore, pre-emergence application of a non-selective broad-spectrum herbicide is an effective and broadly used strategy for weed management (Douglas et al., 2009).

Planting a mixture of bioenergy crops or energy crop and other crops (intercropping) like legumes is also an effective strategy to reclaim marginal land and reduce the cost of nitrogen fertilizers. The only drawback is planting a mixture of species could create competition for water resources and thus reduce biomass yield. A study from the semi-arid region of the Loess Plateau in China concluded that planting switchgrass with other annual crops lower its biomass yield and water use efficiency. Furthermore, no biomass gain was obtained by adapting 2:1 intercropping row-replacement system (Xu et al., 2008).

Growing cover crops on marginal land and harvesting them for bio-feedstock are an effective way for production of biofuel biomass in sustainably way. This strategy has minimal or no effects on food crop production as these crops are terminated and incorporated into land before plantation of food or cash crop and thus increase soil organic content and increase water holding capacity and fertility (Blanco-Canqui, 2016). Thus, these cover crops have two purposes; firstly, they enhance the nutrient supply to the soil, and secondly, they enhance lignocellulose biomass for biofuel production. Land located near edges of rivers and stream is also considered marginal land and these lands are well suited for bio feedstock crop production (Cai et al., 2011; Campbell et al., 2008; Gopalakrishnan et al., 2011). A recent study from Gansu province in Northwest China reported that growing cover crops is one of preferred practice for a sustainable agriculture programme and soil and water conservation (Nong et al., 2020). Crop rotation, another strategy, is an effective approach to sequester C in soil and to enhance soil fertility (Hassink, 1995; Jarecki & Lal, 2003). For example, Alfalfa, as a primary rotation legume, is widely grown for animal feed for the fast-growing livestock industry (Wang et al., 2008) in the Loess Plateau of northwestern China, while also reducing soil erosion and improving soil fertility and quality (Jun et al., 2014). A recent study reported that the lentil–wheat–maize and maize–flax–pea rotations are the most suitable patterns to optimize simultaneous economic and ecological development of arid and semi-arid regions in China (Wei et al., 2020). Likewise, various other legume plants are planted with food and crops to improve soil fertility and characteristics (reviewed in Zeng et al. (2016)). Recent studies show that certain tree-based intercropping systems exhibit multiple benefits for the environment, such as increasing C sequestration and landscape biodiversity (Henry et al., 2009; Palma et al., 2007; Takimoto et al., 2008), as well as for productivity and economic profits (Fang et al., 2005; Graves et al., 2007). A study from a Northwestern Jiangsu

province, China, reported that intercropping poplar with food crops could significantly enhance biomass production and improve carbon sequestration (Fang et al., 2010). Likewise, a comprehensive study about Contour hedgerow intercropping in the mountains of China revealed that it contributes to soil and water conservation, soil fertility amelioration, land productivity improvement, bio-terrace formation and gives more options for income generation based on local resources in mountain areas (Sun et al., 2008).

Finally, reclamation of marginal lands by plantation perennial, cellulosic species is the most effective approach as it not only provides bioenergy but also helps in ecosystem restoration. Similarly, biofuel from these plants emits less GHGs than fossil fuels due to the high content of cellulose in their biomass (Farrell et al., 2006). Many other ecological advantages can be achieved by planting these species on marginal lands including habitats for wildlife, improve soil health, more carbon sequestration and less competition with food crops (Tilman et al., 2006; Williams et al., 2013) as these species require fewer fertilizer and pesticide inputs, slow runoff and increased water infiltration (Mann & Tolbert, 2000; Parrish & Fike, 2005). Therefore, in conclusion, mixed plantation of perennial grasses, short rotation woody crops, deep rooted plants species and addition of fertilizers and manures are the possible ways to reclaim these marginal lands. China's agricultural support policies have significantly contributed to the increased use of agricultural fertilizers through encouraging farmers to bring more land under cultivation (Wu et al., 2019). For instance, the abolition of agricultural tax by the Government of China in 2006 increased the area of wheat, rice and corn by 10%, 2.2% and 2.6% respectively. Much of the added land was newly cultivated marginal land with low fertility (Chen et al., 2010).

A report from the Ministry of Land Resources of China revealed that due to industrialization, desertification and urbanization, China is about to reach the arable red line. Approximately 25 Mha land area in arid regions of China has salinity and drought problems and thus remains uncultivable. Reclamation and proper utilization of saline soils located in arid regions of country has attracted attention from government officials as well as from scientists. Various reclamation efforts have been started to reclaim saline soil in northwest regions of China involving a number of mechanical, engineering, chemical and biological methods (Wang et al., 2013). One approach is plantation of salt hyperaccumulating plant species which can accumulate high concentration of salts in their above ground tissues. Literature review revealed that many plant species, for example, *Suaeda maritima* and *Sesuvium portulacastrum*, have the ability to extract salts from soil and store them in their above ground parts which can later be harvested to remove salts. Another approach is to use drip irrigation systems that can improve water use efficiency in lands located



in arid regions (Ravindran et al., 2007; Wang et al., 2013). These two approaches coupled with various others can be used to reclaim saline marginal lands from various regions of China for bioenergy feedstock cultivation.

## 9 | CONCLUSION

Growing energy crops to produce alternative fuels is a promising option in the face of rising demands for fuels, decreasing available land and competition from food versus fuel scenarios. Crop residues from existing croplands and potential energy crops grown on marginal lands may contribute significantly to feedstock supplies for biofuels in China without reducing food production. Marginal lands account for about 16.8%–17.6% of total land area of China and can produce 17.816–19.373 EJ biomass energy per year. According to recent estimates, China still possess approximately 260 million ha of wasteland which can be used for cultivation of bioenergy crops. Forest and agriculture residues and bioenergy plants account for a significant proportion of biomass feedstock in addition to municipal waste and other sources. Many estimations show that China can increase production potential of energy crops and forest residues by 83% and 38.92% on marginal land by employing effective marginal land use strategies. Although China has developed many effective policies for biofuel production, there is still need for encouraging policies. For effective increase in biomass production, government should allocate more subsidies to the biofuel industry. These subsidies should not only focus on the biofuel production but also benefit procedures like planting, harvesting and transportation. Furthermore, for effective feedstock promotion and utilization of marginal lands, improved agricultural management and landscape planning should be encouraged. Finally, a strong need to search potential bioenergy crops and improvement in available bioenergy crops using advanced biotechnology and molecular biology is required to enhance their adaptability on marginal land.

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## CONFLICT OF INTEREST

Authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

MFQ wrote first draft of manuscript and AW reviewed and helped in the preparation of final draft.

## DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

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