Comprehensive Assessment of Sustainable Potential of Agricultural Residues for Bioenergy Based on Geographical Information System: A case study of China

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Abstract

This study proposes an approach for estimating the sustainable potential of agricultural residue biomass, with the novel characteristic of combining regional annual crop yields, topographic and legislative restrictions, as well as local soil organic matter and soil erosion considerations in the sustainable potential assessment. The proposed approach is applied in the case of China. To ensure accuracy and reliability of the evaluation, the theoretical potential was first calculated based on the residue-to-product ratio (RPR) in China at a regional level. Based on the theoretical potential, a geographic information system (GIS) was then employed to determine the technical potential and sustainable potential of agricultural residues in China. The theoretical, technical and sustainable potential of agricultural residues were found to be equal to 1001.47, 565.82 and 143.20 Mt per year, respectively. Up to 20% of agricultural residues are technically collectable but not currently utilized as resources; if appropriately utilized as an energy source, these residues could generate up to 108 TWh of bio-based power per year. However, for sustainability purposes, the maximum energy potential is limited to 27.8 TWh/year. It was also found that among China's 31 provincial regions, Heilongjiang holds the greatest potential for the establishment of an agricultural residue-based economy by virtue of its resource availability.

Key Words: GIS-based Assessment; Agricultural Residues; Sustainable Potential; China.

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Abbreviations

GIS	Geographical Information Systems
RPR	Residue to product ratio
HI	Harvest index
NBSC	National Bureau of Statistics of China
FAOSTAT	Food and Agriculture Organization statistical database
SE	Soil erosion
SOM	Soil organic matter
RRA	Residue retraining amount

1. Introduction

Energy security has been globally acknowledged as a crucial factor for a national development strategy. The rapid growth in global energy consumption has already heightened concerns over supply difficulties, depletion of resources and environmental impacts [1]. In recent years, the renewable energy sector has developed rapidly, and bioenergy has been identified as one of the major renewable energy sources [2]. The EU has established its renewable energy strategy with the goal of reducing greenhouse gas emissions by 80-95% in 2050 compared with 1990 levels with renewable energy accounting for at least 55% of the gross final energy consumption [3]. Biomass has been anticipated as a major source of renewable energy. Until 2020, China had installed over 29.5 GW of biomass-based power plants and 13.3 GW of this are powered by agricultural residues, which contribute 51 TWh of power supply a year [4]. Despite their availability, agricultural residues cannot be collected from the land without a cost. According to the studies by Monforti et al. [5] and Thorenz et al. [6], extensive collection of residues from the land might have consequences for the depletion of soil organic matter and nutrients (i.e., carbon, phosphorus and nitrogen) and soil erosion, affecting soil fertility and environmental sustainability. Therefore, an appropriate collection rate of agricultural residues, that accounts for different geographical areas according to their characteristics, should be identified to meet the essential prerequisites of economic viability and environment protection.

The availability of agricultural residues can be generally classified into three categories: theoretical potential, technical potential and sustainable potential [6, 7]. The theoretical potential is the maximum annual quantity of biomass that is produced within a certain geographical boundary; this assumes no limitations related to harvesting, economic or environmental constraints [8, 9]. The technical potential is a subset of the theoretical potential and represents the amount of biomass that is technically and economically feasible to collect, depending on the type of residue and the efficiency of the harvesting equipment [7, 10]. The sustainable potential refers to the residues that can be removed from the field while complying with environmental regulations and preventing any adverse impacts on the land such as soil erosion or the depletion of soil organic matter [2]. Various methodological approaches have been applied to estimate crop yield at the regional, national and global scales. The data on crop yield, however, are often insufficient, resulting in large gaps in crop yield estimations [11]. The estimation of residue potential relies on an assumption of the relationship between a crop and its residues. One of the most common methods to estimate residues is the residue to product ratio (RPR), which is the residue weight relative to crop weight [12]. Another residue estimator is the harvest index (HI), which represents the proportion of crop yield relative to the total aboveground crop production (including straw) [2, 13]. It has been widely suggested that the RPR method has an advantage over the HI method [14-16] because actual agricultural production might vary substantially between regions. The estimation of residue yield based on national average crop production might result in substantial uncertainty if the scope of the studied area is large, for example, at the national or continental scale. Therefore, an RPR at a local geographical scale is needed to assign a reliable theoretical potential. Besides, the harvestable quantity of residues can be substantially affected by the working capacity of the harvesting equipment. Previous studies have shown that there could be a loss of 15-25% of the total residue during the harvesting process due to limitations of the harvesting equipment [17, 18]. For example, Weiser et al. [19] estimated the potential agricultural residue in Germany and found that the technical potential is approximately 50% of the theoretical potential.

Extensive residue removal can result in both soil erosion (SE) and the loss of soil organic matter (SOM). Returning residues to the field has various benefits such as reducing soil evaporation, improving water infiltration, enhancing soil fertility, and developing rainfall capture capacity and soil porosity [20-22]. If agricultural residues are to be collected and utilised in a sustainable manner, the removal of residues must be economically viable without impairing soil heath and water quantity [23, 24]. SOM maintenance and SE control are two primary targets of residue retention. The control of SE depends on soil properties, rainfall, topographic characteristics and tillage methods [25]. To accurately determine the quantity of agricultural residues that should be retained in the field to provide sufficient organic matter for subsequent crops, the removal rate should consider the local soil quality (including both SE and SOM) well into the future. Allmaras and Dowdy [26] claimed that 30% residue could prevent 80% of soil erosion. Andrews [27] also suggested that to prevent soil erosion, the maximum removal rate should be no more than 30% of the total theoretical potential. However, using such suggested constant value to account for soil health concerns might result in significantly inaccurate estimations of the sustainable potential of agricultural residues, as the quantity of retentive residues for ensuring soil health highly depends on the specific regional soil conditions.

In European regions, residues are typically left in the field as the principal source of SOM Scarlat et al. [2] estimated agricultural residues from main crops in 36 European countries, which assessed different amount of residues potential by applying geographical information system (GIS), that accounted for the effects of residue removal rates on SOM. However, in regions with intense farming activities such as China, the residues are frequently not returned but instead are burned in the field to rapidly clear the field for further land preparation and planting [27, 28]. Liang et al. [29] investigated SOM concentrations in China and developed a SOM model based on environmental factors such as soil forming factors, local climate and vegetation and determined that the highest SOM values (over 6%) were found in southwestern and north-eastern China, whereas the Northwest had the lowest SOM content. In that study, 2% SOM was set as a baseline for the evaluation of sustainable potential. Due to the local differences, an improved residue removal model is required, with the inclusion of additional parameters such as soil erosion and soil condition, weather conditions, as well as residue losses and moisture content [30]. Ultimately, a gap in the existing literature exists in approaches that collectively consider both local SE and SOM in assessing the sustainable agricultural residue potential, at a higher level of geographical granularity. Furthermore, the evaluation of agricultural residues potential in China has been mostly focusing on the theoretical potential up to now, without in-depth analyses of practical harvesting and environmental restrictions.

Aiming to address the identified gaps, this work proposes a novel GIS-based approach for estimating the sustainable potential of agricultural residues at a high geographical granularity level, considering simultaneously both SE and SOM environmental restrictions in the process. The proposed approach is applied for the case of China, where there is a lack of sustainable potential assessment, allowing a comprehensive assessment of the sustainable agricultural residues potential against the theoretical and technical potential. A precise sustainable harvesting rate has been adopted that reflects the regional crop growth differences (i.e., the regional annual crop production and the regional residue-to-product ratios), considers local topographic and legislative conditions, and accounts for integrated regional environmental restrictions (i.e., SOM and SE) for the first time to evaluate the overall sustainable potential of agricultural residues. In this work, GIS is employed as a decision support system for analysing spatially referenced data, to distinguish the relationships among the disparate data layers, and thus account for topographic and environmental restrictions for the determination of the sustainable potential of agricultural residues in China.

2. Methodology

In this study, a stepwise approach was applied to evaluate agricultural residue potentials. The theoretical potential of agricultural residues was estimated based on the regional annual crop production (CP) and the RPR. To estimate the technical potential of agricultural residues, a spatial technical potential layer was created by splitting the arable land layer from the land cover layer based on GIS data (ArcMap 10.7, provided by Esri) integrated with restrictions on residue collection (the topographic layer from the landform type layer) according to mechanistic capability. This identified the technical potential area. By comparing the technical potential area with the original arable land, the proportion of technical potential was determined. The technical potential of agricultural residues is estimated by multiplying the theoretical agricultural residue by the proportion of technical potential.

The sustainable potential was calculated based on the proportion of the theoretical potential layer in the sustainable potential layer. Arable land from the technical potential spatial layer that did not comply with legislative regulations was not included in the sustainable potential spatial layer. The amount of agricultural residue in the sustainable potential spatial layer can be calculated by multiplying the proportion of the sustainable potential layer by the theoretical potential. The arable land distribution and area under various soil erosion and soil organic matter classifications in the technical potential spatial layer were identified and calculated. The retention rate of residues for individual soil erosion and soil organic matter classifications was guided by a literature review. The total amount of retained residues within the sustainable potential layer was then calculated using the various retention rates and their areas. The sustainable potential was calculated based on the total residue in the sustainable potential spatial layer and the amount of residue retained. Fig. 1 illustrates the methodological approach adopted in this study and the relationships among theoretical, technical and sustainable potentials.

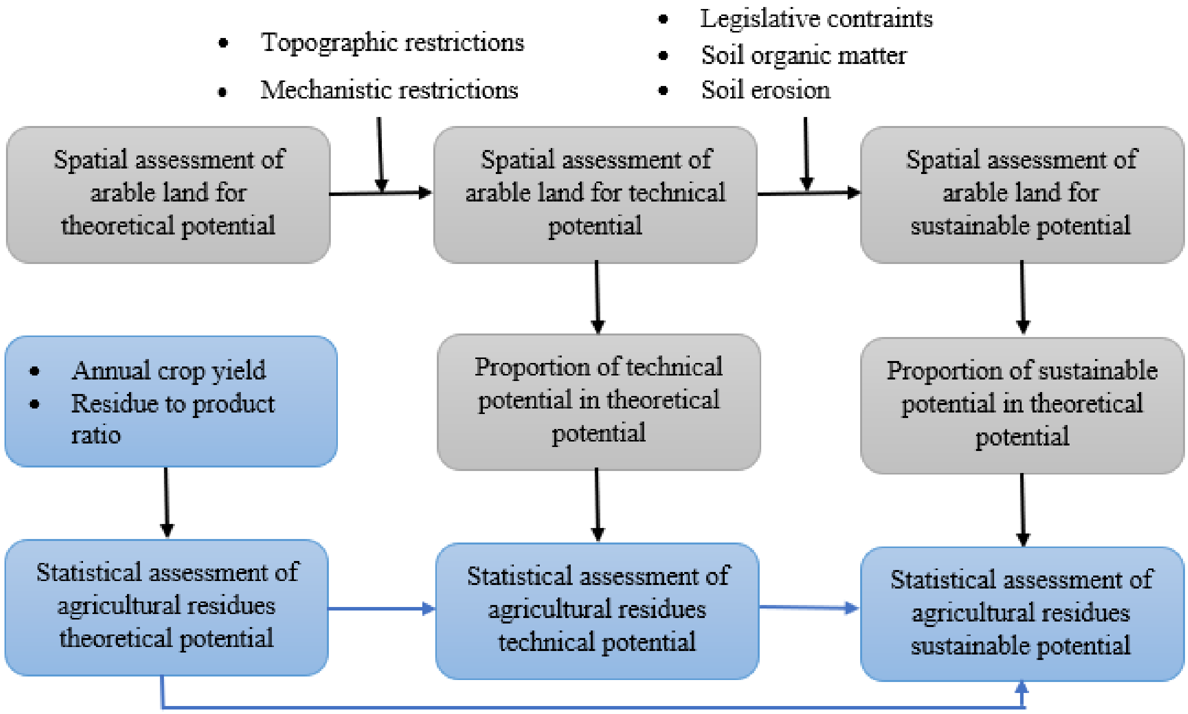


Fig. 1. Process of agricultural residue assessment.

2.1 Arable land area determination

The framework of the integrated GIS-based modelling approach is presented in Fig. 2. The ArcMap 10.6 (an Esri software package) module builder and built-in tools were employed to perform the GIS analysis. The framework for the spatial assessment of arable land included three main approaches. The first step was land cover transformation, classification and mapping. A land use map layer was converted from a raster file to a polygon file to calculate the area of land use. The arable land spatial layer was created by splitting out the corresponding land class from the land use spatial layer. Next, the spatial tool in ArcGIS was used to analyse the resulting arable land layer area; this was compared with statistical data to evaluate its accuracy. Finally, the arable land distribution spatial layer and provincial administrative boundary spatial layer were overlain to generate the arable land distribution by region.

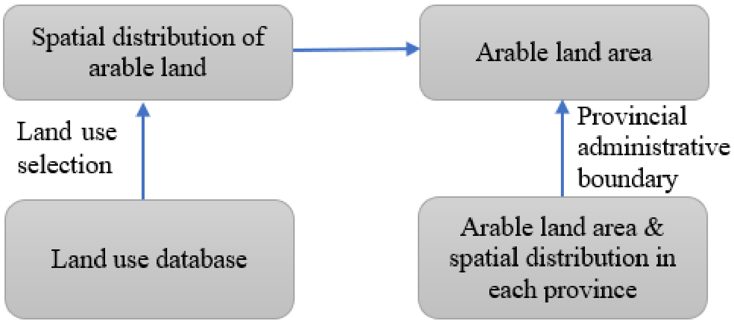


Fig. 2. The process of determining residue potential.

2.2 Theoretical potential assessment method

The theoretical potential of agricultural residues can be estimated from the regional annual crop production of each crop species *i* and the local residue-to-production ratio *RPR (i, j)* using the following equation:

$$RP = \sum_{i=1}^{m} \sum_{j=1}^{n} CP(i,j) * RPR(i,j) \tag{1}$$

where $CP(i,j)$ is the annual production of crop species i in province j and $RPR(i,j)$ is the residue-to-production ratio of crop species i in province j.

2.3 Technical potential assessment method

The technical potential of agricultural biomass was estimated based on topographic restrictions, the working capability of the harvesting machinery and the statistics for theoretical potential. A detailed flow chart is presented in Fig. 3.

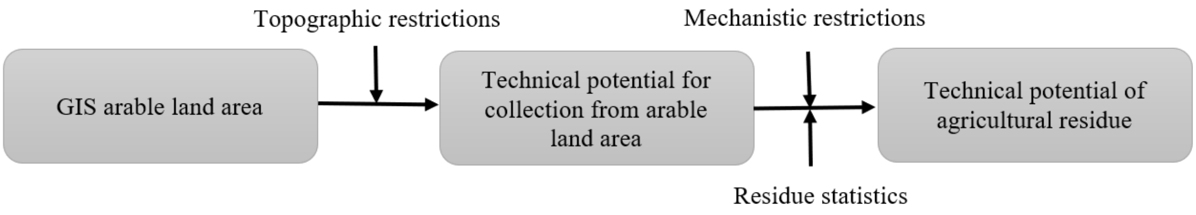


Fig. 3. Process of residues technical potential for power generation

The assessment of technical potential can be divided into two stages: the establishment of the technical potential arable land spatial layer and the area calculation. The arable land area in the technical potential spatial layer was established based on an area-weighting method, which combined arable land and topographic restrictions. First, the spatial topographic layer was collected in a raster format and converted to a polygon format to calculate the area of arable land. Second, the topographic layer was selected and created. Areas with a steep slope (> 15°) were split from the technical potential topographic layer because of severe soil erosion and the difficulty of harvesting. The arable land spatial layer was then overlain with the topographic layer. Once the arable land spatial layer was established, the arable land distribution and area with gentle slopes (≤ 15° for mechanised harvesting), representing the technical potential, were calculated.

Once the area of arable land meeting technical potential requirements was calculated, the proportion of the theoretical potential that had technical potential was estimated. Due to limits on the operation of the collection machinery, a collection rate of 80% was applied based on the average values from the literature [2, 17]. The quantity of residue with technical potential can be calculated from the proportion of technical potential arable area, the theoretical potential and the collection rate.

2.4 Sustainable potential assessment method

The sustainable potential has been estimated as the amount of residue that can be collected without soil erosion, loss of fertility and violation of legislative regulations. To obtain the amount of residue with sustainable potential, it was first ensured that the arable land was not subject to legislative restrictions. Legislative regulations require a protected area with a radius of 500 m around a water body. Within this area, work activities in any type are prohibited [31]. Therefore, the arable land spatial layer with technical potential was overlain with a 500 m area around water bodies to create an arable land spatial layer that included legislative regulations.

Second, to address soil erosion control, the soil erosion is classified as 'weak' 'mild' 'moderate' 'intense' 'strong' and 'severe' in most Countries, regarding to its assessment system. Based on regulations regarding water and soil conservation[32], areas under 'intense', 'strong' and 'severe' soil erosion are not recommended for farming activities. Thus, to obtain reliable data, the erosion classifications of 'weak', 'mild' and 'moderate' were included in this study, and the classifications of 'intense', 'strong' and 'severe' as restriction criteria were not included. To determine the arable land area under the individual erosion types (weak, mild and moderate SE) and its spatial distribution, the arable land area of each class of soil erosion was overlain with arable land from the technical potential layer with legislative restrictions. The amount of residue cover required for soil erosion control was dependent on the erosion grade. Researchers have agreed that 90% soil loss control can be considered adequate erosion control [21, 27, 33]. The amount of residue cover applied in the GIS model is displayed in Table 1.

Table 1. Residue retention standards for different soil erosion classes [27, 33, 34]

Soil erosion classification	**Amount of mulch ($t/km^2/year$)**
Weak	200
Mild	200
Moderate	300

Third, the area of SOM classifications and its retention rate were assessed. SOM plays a crucial role in maintaining soil fertility for sustainable agriculture. Various studies have suggested that the sustainable removal rate of residues ranges from 20% to 40%. Moreover, 2% SOM has been recommended by various researchers as a reasonable criterion for maintaining the SOM balance in agriculture [21, 35, 36]. There is no doubt that not all arable land can achieve a SOM content of 2%. Thus, the residue retention rate (RRR) was calculated using Equations (2) and (3) [20] to tailor this value to local conditions.

If the SOM content in the topsoil (20 cm) is lower than 2%,

$$RRR_{SOM}=80\% \text{ of residue production} \tag{2}$$

and if the SOM content in the topsoil (20 cm) is higher than 2%,

$$RRR_{SOM}=60\% \text{ of residue production} \tag{3}$$

To acquire reliable data, the regional distribution of SOM concentration was analysed and data were introduced from Liu [37]. Thus, the amount of sustainable removal residue can be calculated.

SE and SOM are two criteria for soil health and soil fertility. To estimate the sustainable potential of agricultural residues, it is necessary for the retained residue to meet the maximum requirements of amount of residue retained both for SE and SOM. The total residue retained for SE and SOM were calculated and compared and the maximum retained amount was selecting as the sustainable residue retention. The difference between technical potential, legislative regulations and residue retention is the sustainable potential of the agricultural residue.

The total amount of retained residue is dependent on the properties of the land (soil erosion classification and SOM content) and the applied specific residue retention amount (RRA) (using the larger value) was based on Equations (4) and (5).

If $RRA_{SOM} > RRA_{SE}$:

$$\text{RRA}= RRA_{SOM} \tag{4}$$

If $RRA_{SE} > RRA_{SOM}$:

$$\text{RRA}= RRA_{SE} \tag{5}$$

Thus, the amount of residue with sustainable potential was the difference between the total amount of residue with technical potential under legislative regulations and the amount of residue retained.

3. Results and Discussions: A Case Study of China

3.1 Data collections and input

Statistical data. As stated before in Section 3.2, the annual crop production and residue-to-production ratio were two main factors for the estimation of the residues theoretical potential. As China is a large agricultural country, the types of crops and their annual productions vary in different regions. To access the latest data, annual crop productions were obtained from each province or municipality subordinate statistics bureau, which are part of the National Bureau of Statistics of China (NBSC). Due to the inaccessibility of the websites of subordinate statistics bureaus (Hubei, Hebei, Yunnan, Tibet, Ningxia and Qinghai provinces), some of the data were collected directly from the NBSC's Statistical Yearbook [38]; the data from 16 provinces or municipalities were acquired for the year 2016, and the remaining regions used the most recent accessible online data (2015).

In this work, region-specific RPR is applied for each crop due to no overall RPR data available to represent the major crops in China. The region-specific RPR data for the major crops are summarised in Table 2, including the most common cereals (wheat, corn, rice, millet and sorghum), root crops (tubers), oil crops (peanuts, sunflower, sesame and rape straw) and fibre plants (cotton and other fibre crops). Table 2 shows the RPRs for 6 major regions in China: Northeast (Liaoning, Jilin and Heilongjiang), North China (Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shandong and Henan), the middle and lower reaches of the Yangtze River (Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei and Hunan), Northwest (Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang), Southwest (Chongqing, Sichuan, Guizhou, Yunnan and Tibet) and South (Fujian, Guangdong, Guangxi, Hainan).

Table 2. RPRs for the major agricultural residues.

	Northeast	North	Middle and lower reaches of Yangtze River	Northwest	Southwest	South	Ref.
Wheat	0.93	1.34	1.38	1.23	1.31	1.38	[39]
Corn	1.86	1.73	2.05	1.52	1.29	1.32	[39, 40]
Sorghum	1.60	1.60	1.60	1.60	1.60	1.60	[41-43]
Rice	0.97	0.93	1.28	1.03	1	1.06	[39, 40]
Millet	1.42	1.45	1.66	1.35	1.72	1.66	[39, 40]
Peanuts	1.50	1.22	1.50	1.33	1.20	1.65	[39, 40]
Rapeseed	-	-	2.05	2.34	2.00	-	[39]
Sunflower	2.74	2.16	2.10	1.92	2.10	2.10	[39]
Tubers	0.71	1.00	1.16	1.07	1.05	1.41	[39]
Beans	1.70	1.57	1.68	1.07	1.05	1.08	[39]
Sesame	3.00	3.00	3.00	3.00	3.00	3.00	[42-44]
Cotton	-	3.99	3.32	3.67	-	-	[39, 40]

Note: The RPR of crop species was calculated on an air-dried basis with 15% moisture [39].

GIS-related data. A stepwise approach has been clearly illustrated in methodology, the spatial data for GIS modelling is classified as: land cover, administrative boundary, landform type, and soil erosion, as detailed in Table 3.

Table 3. Spatial data for GIS modelling.

Category	Description	File type	Ref.
Land cover	Remote sensing monitoring data on China's land use status	Raster 1 km × 1 km	[45]
Administrative boundary	China Provincial Administrative Boundary Data	Polygon 1 km × 1 km	[46]
Landform type	Spatial distribution data on landform types in China (1:1 million)	Raster 1 km × 1 km	[47]
Soil erosion	Spatial distribution data on soil erosion in China	Raster 1 km × 1 km	[48]

Due to spatial resolution issues related to layer accessibility, the creation of an arable land distribution spatial layer was based on the land use database and Chinese provincial administrative boundary data at a high spatial resolution (1 km × 1 km). These data came from the Resource and Environment Data Cloud Platform of the Institute of Geographic Sciences and Natural Resources Research [45, 46]. The soil erosion data were collected from the Resource and Environment Data Cloud Platform of China [48]. The classifications and GIS codes for soil erosion are presented in Table 4 and Table 5, respectively.

Table 4. Soil erosion classification.

Soil erosion classification	Average erosion (t/km^2/year)			Soil loss thickness (mm/year)
	Water erosion	Wind erosion	Freeze-thaw erosion	
Weak	<200	<500	<1000	<0.15, 0.37, 0.74
Mild	200	500	1000	0.15, 0.37, 0.74
Moderate	2500-5000			1.9-3.7
Intense	5000-8000			3.7-5.9
Strong	8000-15000			5.9-11.1
Severe	>15000			>11.1

Table 5. GIS code for soil erosion.

	Soil erosion classification					
	Weak	Mild	Moderate	Intense	Strong	Severe
Water erosion	11	12	13	14	15	16
Wind erosion	21	22	23	24	25	26
Freeze-thaw erosion	31	32	33	34	-	-

3.2 Validation of the arable land spatial layer data source

The statistical data from the National Bureau of Statistics of China (NBSC) on annual crop production and the area of arable land were compared with the Food and Agriculture Organization statistical database (FAOSTAT) [49]. It was found that in China, 1658064 km^2 was defined as arable land in 2015, which closely matches the figure of 1663738 km^2 from the NBSC [50]. However, the statistics on crop production from FAOSTAT and NBSC differed: 623.19 Mt was reported by FAOSTAT [51] versus 660.60 Mt reported by NBSC [38]; this difference of 5.67% indicated that the data were reasonably reliable. This comparison was followed by an evaluation of the spatial data. There are two primary errors in GIS mapping: the classification of land cover and the area of a specific land use. Land cover misclassification typically has a high probability in GIS mapping [9]. For example, grassland is misclassified as arable land. Simultaneously, inadequate spatial resolution might overestimate or underestimate the specific land area. To assess the reliability of the GIS mapping data, a single indicator (arable land) analysis was conducted. The accuracy of the GIS mapping for the area of arable land was evaluated using statistical data from NBSC as a reference. The comparison between the NBSC statistical data and the GIS data are presented in Fig. 4.

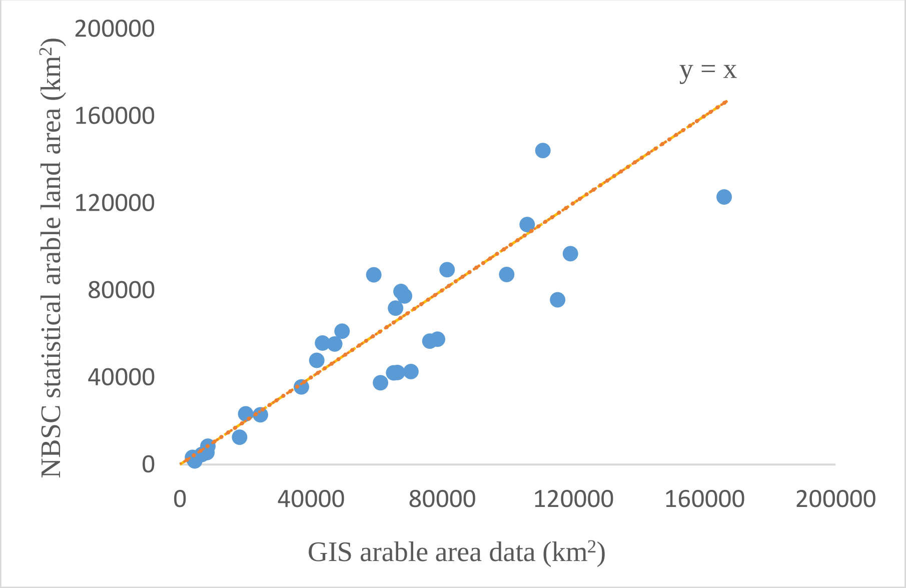


Fig. 4. The arable land difference of NBSC statistical and GIS data of 31 provinces in China.

Fig. 4 shows that the deviation of GIS data on arable land area in each province from the statistical data ranged from 1.74% and 72.73% (deviation= [statistical data-spatial data]/statistical data). To justify the quality of the overall land cover map, a confusion matrix and Cohen's Kappa index were introduced. The confusion matrix is the most common method used to evaluate the overall accuracy of GIS map classifications [52-54]. The principle of the confusion matrix is that cells selected based on the GIS mapping classification are compared with reference data (the actual classification). The confusion matrix contains the predicted class (plot) and the actual class (reference plot). The predicted plot data were selected and covered the most common land use types (agriculture, forest, water and urban) in the GIS map to acquire an unbiased estimation. The reference plot data were visually assessed and divided into a corresponding classification. The confusion matrix was produced by comparing the predicted plot data from GIS layer and the reference plot data to determine the overall accuracy of the GIS maps.

Cohen's Kappa index can be used to measure the classification accuracy, which is derived from the confusion matrix [9, 55]. The Kappa index compensates for the effect of differences in class sizes in the sampled data and are more reliable than a single indicator analysis. The Kappa index is expressed in Equation 6:

$$k = (P_o - P_e)/(1 - P_e) \tag{6}$$

where P_o is the total number of correct predictions of classification in the reference plot (total classification accuracy) and P_e is the proportion of the reference plot correctly predicted by chance under the assumption of independence. A higher Kappa index value indicates better spatial classification. The evaluation standard is presented in Table 6 [56].

Table 6 Cohen's Kappa index assessment [56].

Kappa index	Strength of agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.00	Almost perfect

In this study, 323 plots were selected to analyse the accuracy of the GIS assessment against visual observations, including 149 agricultural lands, 99 forest lands, 52 water areas and 23 urban areas. The results are shown in Table 7. The overall accuracy of land use classification for the 323 plots was over 81% and Cohen's Kappa index was 0.73, which indicates that the layer exhibits satisfactory classification and high quality. However, despite the high accuracy of land use classification, arable land cover is more difficult to classify, due to the low accuracy of arable land recognition algorithm. Beyond that, two main reasons which could affect arable land accuracy are the large object sample and the land cover GIS data updating manner. The main research object was arable land, which accounts 46% of total samples. From the aspect of statistics, larger sample means higher probability of failure. On the other hand, with the development of urbanization, arable land might occupy by other functions, which increased accuracy of arable land recognition on GIS.

Table 7. Assessment of the GIS land use layer

Land type	Total plots assessed by GIS	Actual plots checked by visual observation				Accuracy* (%)	Cohen's Kappa index
		Agriculture	Forest	Water	Urban		
Agriculture	149	98	28	2	21	65.77	0.73
Forest	99	3	93	3	0	93.94	
Water	52	2	0	49	1	94.23	
Urban	23	1	0	0	22	95.65	

*Accuracy = the number of plots with agreement between GIS and visual inspection/total number of assessed plots.

3.3 Theoretical potential of agricultural residues in China

3.3.1 Agricultural residue production and characterization

It was estimated that 1001.47 Mt of residue (air-dried, 15% moisture) were produced in 2017, which is slightly higher than the value of 901 Mt determined by Liu and Li [40] in 2010 and 819.7 Mt determined by Jia et al. [41] in 2014 (Fig. 5). From 2010 to 2017, crop production rose from 559.1 Mt/year to 661.6 Mt/year, which represents an increase of 18.3% [57]. The total amount of residue rose from 901 Mt in 2010 to 1001.47 Mt in 2017, which represents an increase of 11.2%. Thus, the residue result is in consistent with other sources. The agricultural residue decreased in 2014 because the researchers applied an outdated RPR value. In regards to the distribution of crop residue, cereal residues (corn, rice, wheat, sorghum and millet) showed the highest potential with approximately 864.13 Mt of residue (86.27% of the total).

The most promising crop residue was corn stalks, which contributed the majority of the agricultural residue with 440.64 Mt, representing 44% of the total (Table 8). The second and third largest residues were rice straw and wheat straw, which represented 24.11% and 17.62% of the total residue, respectively. Cereal residues were followed by oil crop residues, which accounted for 5.55% of the total agricultural residue in China. The detailed data and references are presented in Table A.1 in the Supplementary document.

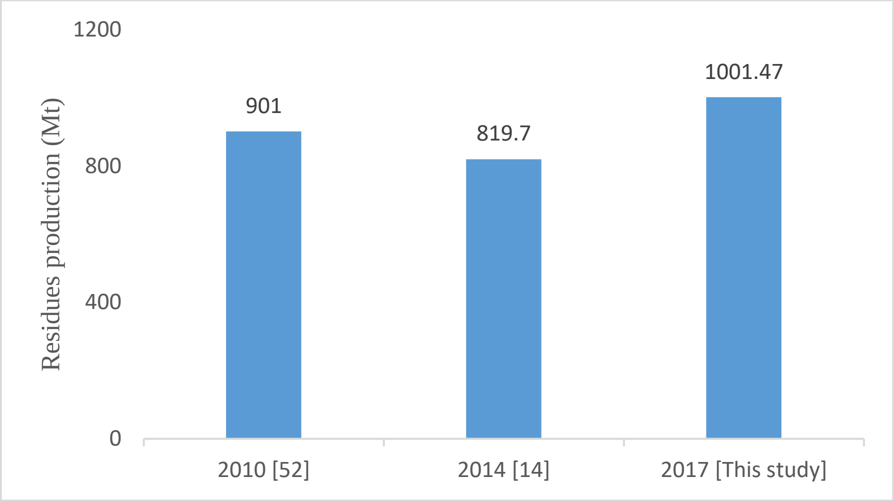


Fig. 5. Theoretical potentials of agricultural residues in China

Table 8. Distribution of theoretical potential of crop residues

	Residues (Mt/year)	**(%)**
Corn	440.64	44.00
Rice	241.45	24.11
Wheat	176.46	17.62
Tubers	30.47	3.04
Beans	28.13	2.81
Rapeseed	27.05	2.70
Cotton	23.15	2.31
Peanuts	21.71	2.17
Sunflower	4.62	0.46
Sorghum	3.22	0.32
Millet	2.36	0.24
Sesame	2.19	0.22
Total	1001.47	100

3.3.2 Spatial distribution of agricultural residue potential in China

There were significant regional differences in agricultural residue potential (Fig. 6). These differences were influenced by local environment, economic development, topography and agricultural production. The agricultural residue resources were primarily located in the North, the middle and lower reaches of the Yangtze River and north-eastern China. Those three districts accounted for over 79% of the residue resource. Among these, North China was the most promising district, producing 329.83 Mt of agricultural residue per year (33% of total). South China produced the smallest fraction of the residue.

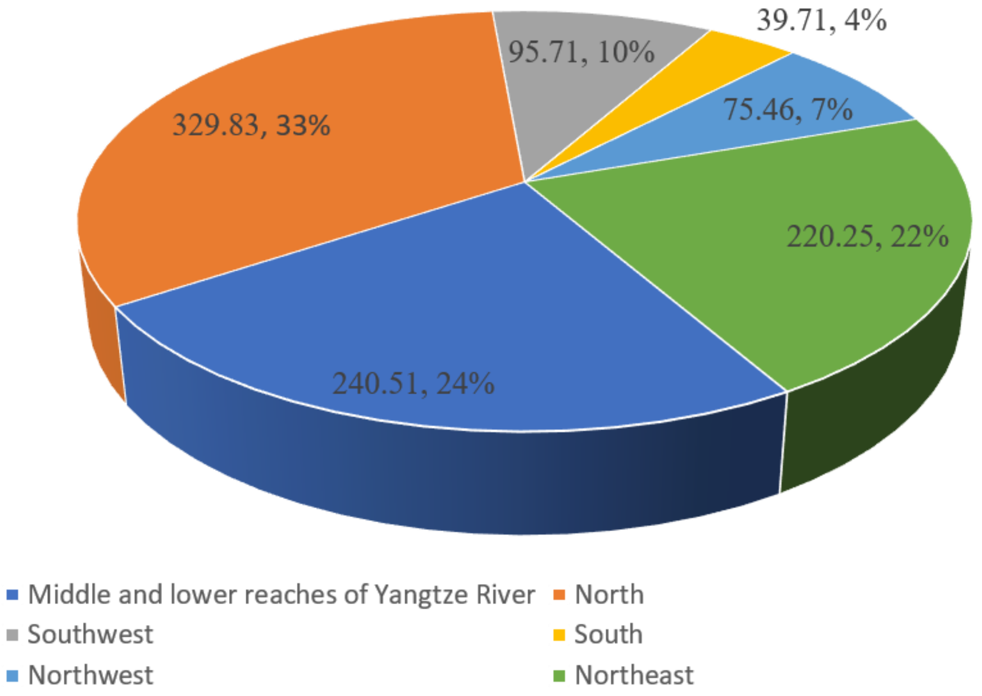


Fig. 6. Spatial distribution of theoretical potential of agricultural residues.

From Fig. 7 and Table 9, it can be seen that the agricultural residue is primarily found in the North of China, particularly in Heilongjiang, Henan and Shandong Provinces, which accounted for 110.04, 100.65 and 86.48 Mt, respectively. One of the main reasons for the high level of residue in these areas is the widespread cultivation of corn. As a C4 photosynthetic species, corn stalks have a higher residue yield [17], which is almost twice the weight of the grain.

The production of corn stalks is concentrated in northern China, particularly in the Northeast, which includes Heilongjiang, Jilin and Shandong Provinces and accounts for 39.8% of the total amount of corn stalks (Fig. 7). Rice requires large amounts of water to supply its growth; southern China has abundant rain, which creates an appropriate growth environment for rice. Thus, rice straw is concentrated in southern China, particularly in the Southwest in areas such as Hunan, Jiangxi and Hubei (which accounted for 36.0% of the total rice straw residue). The climate contributes to abundant water resources and high-quality soil resources in Heilongjiang, which make it a satisfactory source of rice straw (27.35 Mt per year, 11.3%). Wheat is a traditional food source in northern China. Thus, the wheat straw residues are higher in northern China than in other regions. The wheat straw resources were high in Henan, Shandong and Hebei (28.1%, 18.9% and 11.4%, respectively).

Table 9. Theoretical potential of agricultural residues in the top 10 provinces.

Province	**Theoretical potential (Mt/year)**	**(%)**
Heilongjiang	110.04	10.99
Henan	100.65	10.05
Shandong	86.48	8.64
Jilin	70.25	7.01
Hebei	59.72	5.96
Inner Mongolia	56.58	5.65
Anhui	54.10	5.40
Jiangsu	50.13	5.01
Hubei	46.86	4.68
Hunan	45.71	4.56

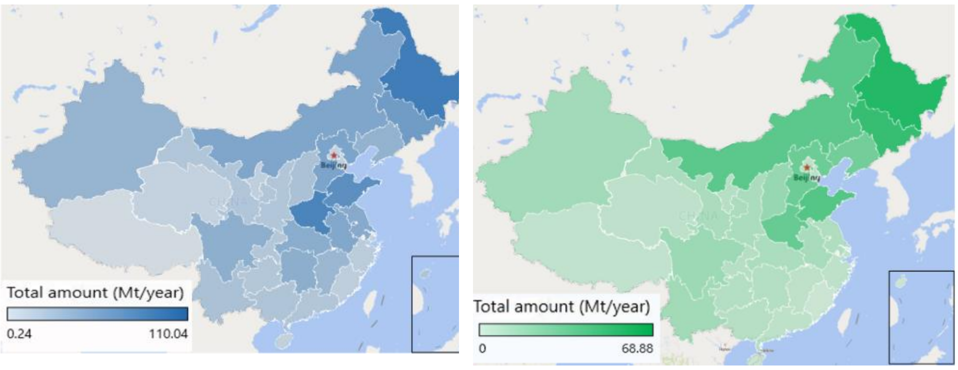
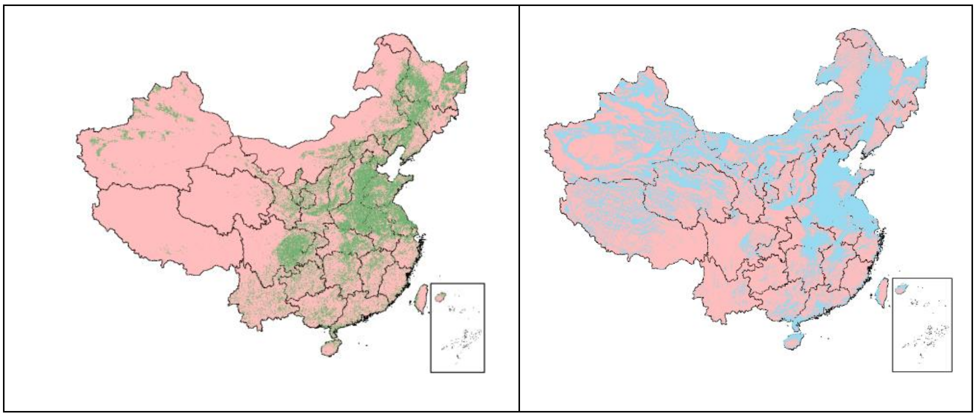


Fig. 7. Top left, (a) distribution of total agricultural residue potential; top right, (b) corn stalk distribution; bottom left, (c) rice straw distribution; bottom right, (d) wheat straw distribution.

3.4 Technical potential of agricultural residues in China

The assessment of the technical potential of agricultural residues was performed in 2 steps. First, the collectable technical potential in the arable land spatial layer was evaluated based on the slope of the land using GIS data. This was followed by the introduction of statistical data on economically available arable land to determine the technical potential of the residue.

The green area in Fig. 8 (a) shows the arable area in China. Due to the influence of local climate and precipitation centred in the east, the arable land was concentrated in eastern China. However, topography was another constraint on the distribution of arable land. Mechanised harvesting can occur on gentle slopes; in Fig 8 (b), the major of the gently sloping land is located in North and Northeast China, which results in a higher level of crop production and residue potential. The available collecting area was generated by considering both the distribution of arable land and the topographic distribution, which is illustrated in Fig. 8 (c).



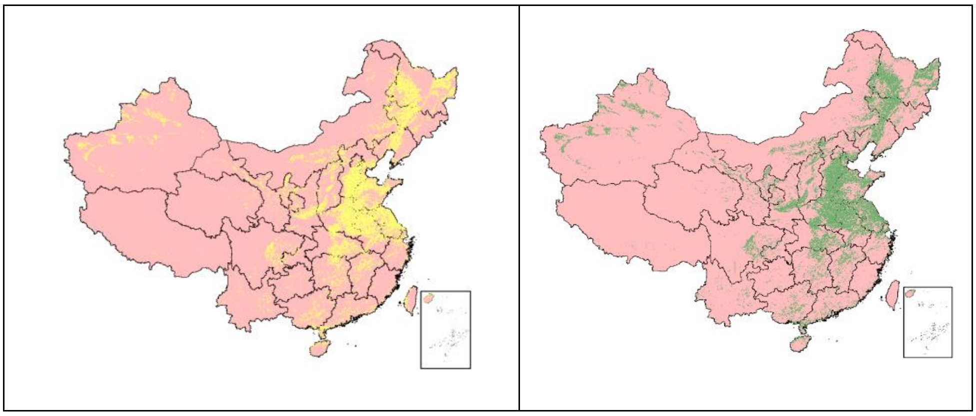


Fig. 8. Top left, (a) distribution of arable land in China; top right, (b) distribution of gentle slopes; bottom left, (c) available arable land under topographic restrictions; bottom right, (d) distribution of arable land under legislative regulations.

Of the total arable land, 64% (1070020 km^2) was identified as having technical potential (Table 10). The remaining 36% of arable land was not considered in this study due to the steep slope and the resulting difficulty in collecting residues. Due to the heterogeneity in topography, the distribution of arable land in each province may differ. Thus, the amount of residue depends on the economically available arable land area. The technical potential of residues under available arable land was 707.28 Mt per year, which accounts for 70.62% of the total residue. The detailed arable land availability and its residue potential for each province is presented in Table A.2 of the Supplementary document. As previously mentioned, the collection capability was set at 80% of residue that can be collected from the field, which results in 565.82 Mt of residue that can be collected on an annual basis. The remaining 20% is left in the field as fertilizer.

Table 10. The technical potential of agricultural residue in China.

	Arable land size (km^2)	Residues potential (Mt/year)
Total arable land (theoretical potential)	1663738	1001.47
Arable land under technical potential restrictions	1070019	707.28
Residue technical potential (80%)	-	565.82

3.5 Sustainable potential of agricultural residues in China

In this section, the arable land that also meets the environmental restrictions is calculated. Because soil erosion and SOM were introduced as restrictions via GIS, the sustainable potential of the residue was lower than the technical potential.

3.5.1 Arable land with legislative regulations (water protection areas)

Fig. 8 (d) shows the distribution of available arable land under legislative regulations, which require harvesting activity to be at least 500 m away from any water body. To satisfy this regulation, the arable land was further reduced from 1070020 km^2 to 1060092 km^2, and the amount of residue decreased by approximately 0.83% from 565.82 Mt to 561.15 Mt per year (Table 11). The arable land in the individual provinces is presented in Table A.3 of the Supplementary document.

Table 11. Residues with sustainable potential under legal regulations.

	Arable land size (km^2)	**Residues potential (Mt/year)**
Technical potential	1070020	565.82
Under regulation	1060092	561.15

3.5.2 Arable land with soil erosion

Fig. 9. Left, (a) arable land under weak soil erosion conditions; middle, (b) arable land under mild soil erosion conditions; right, (c) arable land under moderate soil erosion conditions.

The spatial distribution of soil erosion and the statistics on arable land soil erosion were determined and are shown in Fig. 9 and Table 12. Over 97.7% of the arable land under legislative regulation was considered environmentally friendly, which represents approximately 1035844 km^2. Of this area, 887140 km^2 of arable land was located in areas with weak soil erosion and produced 465.51 Mt of residues annually, and 93566 km^2 was located in areas with mild soil erosion and produced 53.24 Mt of residues per year; 30.62 Mt of residue was produced annually on 55139 km^2 of arable land with moderate erosion.

Table 12. Soil erosion for arable land and corresponding residue potential.

	Arable land size (km^2)	Residues potential (Mt/year)
Weak soil erosion	887140	465.51
Mild soil erosion	93566	53.24
Moderate soil erosion	55139	30.62
Total	1035844	549.37
Under legislative regulation	1060092	561.15

To prevent soil erosion, mulch is applied to arable land. For land that is defined as having weak or mild soil erosion, 200 t of residue needs to be returned to the field per square kilometre. For moderate soil erosion, the quantity of residue is 300 t. A total of 20% of residue is returned to the field as a result of the operation of the harvesting machinery; the additional amount of residue that needs to be returned is presented in Table 13. To prevent soil erosion, 212.68 Mt of residue is required each year, of which 177.43 Mt is baseline mulching to prevent weak soil erosion. For mild and moderate soil erosion, the total amount of residue was less than that for weak soil erosion because of smaller area of arable land in these erosion classes (18.71 and 16.54 Mt, respectively). Therefore, the total available residue potential under soil erosion conditions was 336.69 Mt annually.

Table 13. Residue potential and requirements under soil erosion.

	Arable land area (km^2)	Residues potential (Mt/year)	Residues left in field (Mt/year)	Total residues required for mulching (Mt/year)	Deficits (Mt/year)	Available residues (Mt/year)
Weak soil erosion	887140	465.51	116.38	177.43	61.05	288.08

Mild soil erosion	93566	53.24	13.31	18.71	5.40	34.53
Moderate soil erosion	55139	30.62	7.66	16.54	8.89	14.08
Total	1035844	549.37	137.35	212.68	75.34	336.69

3.5.3 Arable land with adequate soil organic matter (SOM)

To maintain soil fertility and SOM balance, residues must be returned to the soil. As mentioned previously, an accepted value for SOM ranges between 1% and 3% as a sustainable standard, and the 2% SOM selected in this study is within this range. Approximately 84.6% of the arable land available for collection was assessed a SOM value of less than 2%, which represents 406.26 Mt of residue per year; therefore, 143.2 of the 561.15 Mt of residue is available for another use, as shown in Table 14.

Table 14. Residues potential and requirements for SOM.

	Arable land area (km^2)	Residues returned to field (Mt/year)	Residue availability (Mt/year)
SOM ⩾ 2%	162913	92.93	61.95
SOM < 2%	897179	325.01	81.25
Total	1060092	417.94	143.2

SOM and SE are two critical factors for soil fertility. Sustainable residue removal should meet both SOM and SE requirements. Because the amount of residue retained for SOM is higher than that for SE, the residue availability under SOM requirements can be considered the sustainable potential of the agricultural residue. Thus, the agricultural residue with sustainable potential in China was 143.2 Mt annually, which is 14.3% of the theoretical potential and 25.3% of the technical potential.

3.6 The sustainable potential of agricultural residue for green power

This study assessed the potential of agricultural residue in China, which includes the theoretical potential, technical potential and sustainable potential. In 2017, the theoretical potential was

10001.47 Mt agricultural residue, and the technical potential was 565.82 Mt, which is approximately 56.5% of the theoretical potential. To ensure environmental sustainability, the sustainable potential was downsized to 143.20 Mt, as shown in Fig. 10.

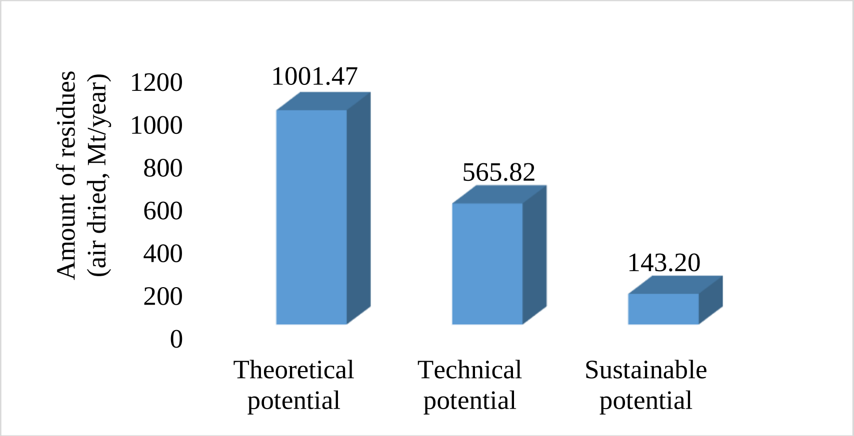


Fig. 10. Theoretical, technical and sustainable agricultural residue potential in China.

The agricultural residue was estimated on the basis of air-dried RPR with a moisture content of approximately 15%. The theoretical, technical and sustainable potential residues available for green power generation were 851.25, 480.95 and 121.72 Mt/year, on dry basis, respectively.

The heating value is an important criterion for the evaluation of power generation. The heating value is defined as the heat released during combustion [58]. The heating value can be classified as a lower heating value (LHV) or a higher heating value (HHV). The difference between the LHV and the HHV relates to whether the energy in the water vapour is considered as part of the unit output during energy generation [59]. In power generation, the energy in water vapour is not considered. Thus, the LHV is applied in power generation calculations. The average LHV value of crop residues reported in the literature is shown in Table 15.

The theoretical, technical and sustainable potentials translate to 1.39×10^4 PJ, 7.81×10^3 PJ and 1.99×10^3 PJ of energy per year, respectively. In general, the efficiency of power generation ranges from 20-25% [60-62]. Thus, the 7.81×10^3 PJ of residue (technical potential) that can be collected represents between 1.56×10^3 PJ and 1.95×10^3 PJ of power annually, which can produce at least 433.3TWh to 541.7 TWh per year (assuming 3.6 MJ = 1KWh). To ensure environmental sustainability, agricultural residues converted to power should remain within the range of 111.1 TWh and 138.9 TWh (0.40 $\times 10^3$ PJ to 0.50$\times 10^3$ PJ) per year.

Table 15. The lower heating value of major crop residues in China.

	LHV (db, MJ/KG)	Reference
Corn	13.54	[63-66]
Rice	15.14	[67, 68]
Cotton	13.39	[64, 65]
Wheat	14.39	[64-66]
Sorghum	15.99	[69-71]
Peanut	13.72	[72, 73]
Sesame	14.55	[74]
Sunflower	14.41	[75]
Millet	16.09	[75]
Tubers	14.24	[76]
Beans	15.96	[77]
Rapeseed	15.59	[74]

Because agricultural residues are utilized not only for power generation but also have uses in other industries (such as for forage, industrial materials and bioenergy), unutilized residues are limited. According to the press office of the Ministry of Agriculture, 20% of collected residues are abandoned [78]. Thus, 20% of the technical potential calculated for power generation in the study is actually available. Between 86.67 and 108.34 TWh of power could be produced annually if the abandoned residues were recycled for power generation. This represents 1.58% of the national energy consumption in 2018 (6844.9 TWh) [79]. A conservative estimate is that the available sustainable agricultural residue potential could be converted to between 22.2 and 27.8 TWh per annum.

4. Conclusions

A three-step GIS-based approach involving the evaluation of theoretical, technical and sustainable potentials for agricultural residues has been proposed in this work, with the novel characteristic of considering simultaneously regional annual crop yields, topographic and legislative restrictions, as well as SE and SOM environmental restrictions at a regional level. The proposed approach was applied to assess the sustainable potential of agricultural residues available for potential power generation in China. This approach provides a detailed assessment of residue potential and its provincial distribution using the latest crop production statistics and high-resolution GIS digital spatial data. It was found that 1001.47 Mt of residue is produced annually, including corn stalks (440.64 Mt), rice straw (241.45 Mt) and wheat straw (176.46 Mt). The retention of residues plays a crucial role in reducing soil erosion and increasing soil organic matter and nutrient (such as carbon, nitrogen and phosphorous) sequestration to maintain soil quality. Due to the long-term indiscriminate removal of residues, the density of soil organic matter is far below the standard level in much of China, which leaves only 143.20 Mt of residue that can be considered as sustainable potential of agricultural residues, which could produce from 22.2 to 27.8 TWh each year. This result demonstrates the benefits from adopting the proposed approach for a more realistic sustainable potential assessment. This study indicates that, among China's 31 provincial regions, Heilongjiang holds the greatest potential for the establishment of an agricultural residue-based economy by virtue of its resource availability.

This work contributes to academia by proposing the sustainable potential assessment approach that can be applied to any geographical context. The work contributes also to practice and policy making, since the application of the approach in the case of China highlights the large difference between the theoretical, technical and sustainable potential, that fully accounts for the regional differences in annual crop yields, the local topographic, legislative and environmental restrictions. The outputs can be used by practitioners engaged in the bioenergy value chain to identify areas where there is sufficient sustainable potential to exploit, and by policy makers to ensure that any incentives are focusing on areas where exploitation of the agricultural residues will not lead to environmental degradation, in terms of soil erosion and soil organic matter loss. To maximise the value of these sustainably available agricultural residues, further work will continue to assess its potential for the production of high value-added chemicals or materials.

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