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Review

Straw Utilization in China—Status and Recommendations

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Abstract: As the world's largest grain producer, China's straw yield was 700 million tonnes in 2014. With a national utilization rate of 80% in 2015, there is still a large amount of straw burned in open-field, resulting in air pollution and a reduction in the quantity available as a source of bioenergy. This paper conducts a literature review of success stories and major challenges in comprehensive straw utilization in and out of China. It is noted that nationwide long-term feasible and sustainable straw utilization at a high rate is a highly complex operation, involving most societal sectors, many people and facilities often at different regions. Scenarios were analyzed to estimate the energy potential and air emission reductions China would accomplish in 2020 by converting an additional 5 or 10% of straw-yield to biofuel. Currently, the approach to control straw burning in China is primarily administrative, relying heavily on prohibition and penalties, inconsistent across policy areas and geography, and lacking in long-term planning. Consequently, the effectiveness of the current approach is limited. The main cause of burning is a lack of infrastructure, effective preventive measures, and viable alternatives. Recommendations aimed at promoting a circular bio-economy around using crop straw as resources were provided, including improving straw utilization rates and reducing open-field burning.

Keywords: straw; agriculture residues; biomass; bioenergy; bio-economy; circular economy; China

1. Introduction

China ranked first in the world in 2014 [1] in grain production. The annual grain yield was approximately 607 million tonnes in 2014 [2], while the straw (also known as agriculture residues or crop straw) production was 700 million tonnes [3]. Since ancient times, there have been many usages of straw, like fuel, fertilizer, domestic animal feed, and material for furniture, baskets, buildings, and river dams. The national straw utilization rate in China was approximately 80% in 2015 [4]. One of the challenges is different consciousness levels of farmers toward straw utilization in different regions. Another is the practicality of straw utilization in situ or removal from the field within a very short window between harvesting and planting a subsequent crop, especially in southern China, where two or three crops per year are common. Consequently, some farmers reluctantly resort to straw burning in the field as an easy option, leading to air pollution.

After decades of research and development, straw utilization techniques are becoming more practical and economical. As an integral part of the bio-circular economy, straw utilization leads to energy saving and reduced emission of air pollutants. The economic values and environmental benefits of straw utilization are well-known. Nonetheless, efforts in many aspects are needed to realize such potential, including technology advancement, improvement in education programs, as well as development and implementation of financial and environmental policies. The objectives of this paper are, (1) to review straw utilization issues on a global scale, (2) to analyze the status of straw production and utilization in China in the past three decades, (3) to summarize major regulations and representative policies, and to discuss challenges related to straw utilization, and (4) to make recommendations to improve straw utilization in China.

2. Methodology

The literature survey was performed by searching the internet and university collections. The primary target sources of publication included scientific journals, theses, dissertations, and government or organization reports. The publications were limited to English and Chinese, and the time period of 2009–2018 was prioritized. The major keywords used were "straw", "crop residues", "biological residues", "straw utilization", "biomass", "bioenergy". Five major crops were included in this review. They are rice, wheat, maize, beans, and rapeseed. The yield of these five crops accounted for 92% of China's total annual production during 2007–2009 [5].

3. Straw Utilization Globally

Straw utilization rate is low in some developing countries where open-field burning is the most common practice for straw disposal [6]. In Philippines, India, Egypt, and Thailand, where rice is the predominant crop, the percentages of rice straw burned in the field were approximately 95% (2002–2006) [7], 62% (1999–2000 and 2004–2005) [7], 53% (2013) [8], and 48% (2002–2006) [7], respectively. In China, it was estimated that 62% of the total straw was burned in the field during 1995–2005 [9]. In contrast, straw burning is a rare practice in the United States. Based on the 2014 crop acreage data [10] and estimated acres of crop residual burned in that year [11], the percentage of area burned was 0.6%.

3.1. Air Pollution Caused by Straw Burning

Air pollution is one of the environmental impacts of straw burning [1–3,7,11–14]. Estimation of emissions from open-field straw burning has been carried out at national levels, for example, in India, Thailand, the Philippines, US, and China, using emission factors and quantity of straw burned. Three greenhouse gasses (GHG), CO_2 (carbon dioxides), N_2O (nitrous oxide), and CH_4 (methane), and thirteen air pollutants, CO (carbon monoxide), NMHC (non-methane hydrocarbons), NO_X (nitrogen oxides), SO_2 (sulfur dioxide), TPM (total particulate matter), $PM_{2.5}$ (fine particulate matter), PM_{10} (coarse particulate matter), PAHs (polycyclic aromatic hydrocarbons), PCDD/F (polychlorinated dioxins and furans), BC (black carbon), OC (organic carbon), NMVOC (non-methane volatile organic compounds), and NH_3 (ammonia), were included in those studies [7,11,13].

3.2. Benefits and Disadvantages of Returning Straw to Field

As an alternative to burning, a proportion of straw could be left on the ground or incorporated mechanically into the soil, which minimizes soil erosion as well as nutrient (e.g., organic matter, phosphorus, potassium, calcium, and magnesium) and water losses [15,16]. The nutrient contents vary among different types of straw. The fertilizer values (N, P_2O_5, and K_2O) of wheat straw are higher than those of corn stalks and soybean straw (see Table S1) [17]. The optimum amount of straw left on the field depends on geographic factors, weather conditions, crop types, tillage practices, and harvesting styles [15,16]. In the US, it was estimated that between 1–8 Mg/ha of corn straw should be left on the field to keep soil erosion at acceptable levels [16]. For corn fields in Iowa, it was suggested that at least 2.5 and 4.9 Mg/ha of corn straw should be kept, for the typical no-till and tilling operations, respectively [16]. One of the disadvantages of returning straw to the field is incomplete decomposing of straw due to insufficient time for biodegradation, consequently hindering root penetration. Furthermore, crop pest infestation may be aggravated by straws which provide favorable living places [18]. Another negative impact of a straw return to the soil is increasing GHG emissions. Based on their literature review, Li et al. [18] reported increased rates of CH_4 emissions ranging from 22–210%, due to stimulation by straws.

3.3. Straw Utilization Technology and Commercialization

Technology advancement in straw utilization leads to increased product yields, improved quality, and reduced costs [15,19]. For example, pentose fermentation process results in higher ethanol yields in comparison with hexoses fermentation [15]. In the pulp and paper industry, a cellulose extraction method called “hydrodynamic cavitation” is faster (reducing extraction time from 1–4 h to 10–60 min) and less energy intensive by lowering the temperature from 150–180 °C to ambient conditions [19].

Commercial scale straw utilization has been realized in many countries, such as the US, Europe, and Brazil [20]. In Crescentino (Italy), a plant began production in 2013, converting local wheat straw, rice straw, and Arundo donax to ethanol. The annual production capacity in 2013 was 75 million liters of cellulosic ethanol, making it the world’s largest advanced biofuels refinery at that time. Brazil’s first commercial-scale cellulosic ethanol plant, at São Miguel dos Campos, Alagoas, was in operation in 2014, with an annual capacity of 83 million liters. The feedstock is an agricultural waste, including straw and bagasse. In the US, the Abengoa Bioenergy Biomass of Kansas opened its commercial plant in 2014. A mixture of agricultural waste, non-feed energy crops, and wood waste are used to produce cellulosic ethanol (100 million liters /year) and renewable energy (21 MW).

Another area of straw utilization is briquetting. Loose agriculture waste biomass is converted to high-density compacted green fuel. In 2018, a straw briquetting plant was established in El Sharkia (Egypt). The project is a joint Austrian-Egyptian initiative, with a capital investment of 26M USD. The design capacity is 50,000 tonnes per month. The bulk of products is expected to be exported to the European Union (EU). The total costs for briquette production vary significantly among regions. However, the costs are 30 USD/tonne in general. Brazil and India have established a commercial basis for briquetting. However, the profit margin is thin [21].

In Europe, there have been many efforts toward utilizing straw as an energy resource. Denmark, for example, has been utilizing pellets, wood chips, and straw in heat and power plants, medium-sized industrial boilers, and private homes for many years [22]. Avedøre Power Station, the largest power station in Denmark, has been producing electricity from wood pellets and straw since 2016. One of the plant’s two units has a straw-fired boiler [23]. The Amager plant in Copenhagen, with an electric generation capacity of 314 MW and a heat capacity of 583 MW, has reopened its Unit 1 after retrofitting in 2009, using approximately 380,000 tons (344,730 tonnes) of wood and straw pellets annually [22]. Unit 8 of Fynsverket, a combined heat and power plant in Odense (Denmark’s third-largest city), has replaced 100,000 tons (90,718 tonnes) of coal per year with straw. The unit has an electric capacity of 35 MW and a heat capacity of 110 MW [22].

In March 2007, the EU’s Renewable Energy Directive set a target of 10% transport fuels from renewable energy sources by 2020 [24,25]. As of 2016, this 10% target was achieved only in Sweden and Austria [26].

3.4. Feasibility Analysis of Straw Utilization Projects

Due to the high capital investment costs and low-profit margin in straw utilization, analyses have been conducted to evaluate the economic feasibility of straw utilization projects. Factors considered include costs of straw collection [27], transportation [27–29], and biochemical pre-treatment processes [30]. Studies have shown that straw collection and utilization may be economically infeasible (i.e., the economic balance becomes negative) at distances where transport costs become overbearing. Such distances depend on many factors, including the market price of straw, government subsidies, fuel economy, and fuel price. A case study in Thailand has estimated that with a market price of 25 USD per metric ton and without government subsidies, utilization of rice straw is no longer economically feasible at a transportation distance beyond 90 kilometers. Once the price of rice straw falls below 24

USD (including any applied government subsidies), utilization of rice straw will be infeasible at any transportation distance [31]. Findings suggest that straw utilization costs can be reduced by obtaining straw directly from farmers [32] and optimizing the transportation routes and the numbers and sizes of transportation units [28].

3.5. Straw Utilization Needs Policy and Capital Support

Industrial scale straw utilization requires proper supply chain, production plants, and distribution/storage infrastructure, resulting in high capital cost and operation cost (e.g., transportation) [27,29,32–34]. Therefore, government policies, such as mandatory biofuel-conventional fuel blends [35] and tax incentives [36], are essential to the economic sustainability of the industry.

As the world's largest fuel ethanol producer, US biofuel manufacturers receive substantial subsidies. The tax incentive was up to 1.01 USD per gallon of second-generation biofuel until the end of 2016 [36]. In Argentina, gasoline and diesel have been required to be blended with 5% biofuels since January 2010. Biodiesel and ethanol sold in its domestic market received government financial support as well [35].

First-generation (i.e., agricultural crop-based) biofuels have benefited greatly from tax incentives and other policies. However, the production costs of second-generation biofuels (such as lignocellulose-based ones) are higher. Thus, it is more challenging for second-generation biofuels to be cost-competitive with petroleum fuels [37].

4. Straw Utilization in China

By 2015, the comprehensive straw utilization rate had reached 80% [4]. The remaining 20% was burned in the field or wasted, a noticeable decrease from the 2008–2009 level of 26% [38]. Approximately 29% of the total straw was returned to the soil in 2009, and the rate has been increasing gradually since then [18]. However, the utilization rates differ greatly among regions [13] owing to different levels of policy and financial support, the consciousness of farmers, as well as economic and industrial development.

4.1. Straw Utilization Technology and Commercialization

In recent years, there have been continuous innovations in and applications of straw utilization technology in China. Some examples are in situ decomposition, production of roughage, biomass fuels, biogas, straw-fired power/heat generation, straw board, and paper [39]. The following examples showcase the bioenergy projects implemented by different sectors, including energy companies, farmers, and local governments.

One of the large straw-based biogas projects is carried out in Ar Horqin Banner, Inner Mongolia, with an investment of $\sim$ 50 million USD and an annual processing capability of 55,000 tonnes of corn straw. The plant produces 10.8 million cubic meters of natural gas (methane) and 50,000 tonnes of organic fertilizer per year. Using a life-cycle energy consumption and greenhouse gas emissions approach, it was demonstrated that GHG emissions from this corn straw-based bio-natural gas (BNG) plant (for both vehicle and non-vehicle energies provided by BNG, and fertilizer as co-product) were up to 99% lower in comparison with its fossil-fueled pathway. The latter includes fossil natural gas for non-vehicle energy supply, gasoline for vehicles, and fertilizers from conventional manufacture facilities [40].

Household biomass stoves have been employed by many farmers. Those stoves are fueled with straw or straw briquetting, for cooking and space heating. The newly advanced semi-gasification biomass stoves in the Chinese market can burn crop straw pellets, corn cob, branches, and firewood. The combustion is nearly complete, leading to low air emissions [41]. In addition to reducing the consumption of fossil fuels, biomass stoves improve air quality in the kitchen and living area, thus protecting the health of the farmers. Test results indicate that the thermal efficiency of high-quality household biomass cooking stoves ranged from 35% (corn straw) to 41% (straw briquette), much higher than those of conventional stoves (10–12%). Furthermore, the particulate matter (PM) emission rates were much lower (35 mg/m^3 for corn straw, 38 mg/m^3 for straw briquette) than conventional stoves (>120 mg/m^3) [42]. Laboratory studies have quantified emission factors of straw burning for space heating in rural China. It was found that in comparison with the traditional system, both maize-straw pellet and the advanced stove (fired with maize straw) with an air distribution system significantly reduced air emissions of $PM_{2.5}$, OC, EC (elemental carbon), and water-soluble ions [14].

Straw-fired boilers for heat production have been implemented as well. In Liaoning, the first straw-fired boiler has been in operation since 2016, providing heat for an office building (2400 m^2). The cost is approximately 50% lower than using coal [43]. In Baodi, Tianjin, a space-heating project (23,000 m^2) was implemented in 2017. There were five straw-fired boilers, collectively consuming 1500 tonnes of rice straw during the four-month heating season [44].

4.2. Air Pollution Caused by Straw Burning

In China, the estimated annual emissions of $PM_{2.5}$ and CO_2 from crop residue open burning were 1.4 million tonnes and 144 million tonnes, respectively, in 2009 [45]. Advancements have been made in detection, emission factor testing, emission inventory, and impact assessment of straw burning. Satellite images have become an effective tool to monitor straw burning. However, once the location of a fire spot is identified by a satellite, other sources of data are needed to distinguish between forest fires or straw burning [11–13].

In autumn of 2015, northern China suffered severe air pollution episodes accompanied by widespread haze, attributable to weak atmospheric mixing due to weather conditions and a large-scale straw burning in many regions [12]. Ministry of Environmental Protection (MEP) reported a 16% increase in straw burning incidence in early October of 2015 compared with the same period in 2014, and satellite detected a total of 376 suspected straw burning spots [46].

A study investigated the impact of wheat straw burning on air quality in Beijing. The North China Plain was identified as the main source of pollutants induced by wheat straw burning. The southwestern air flow was the dominant transport path. The impact of wheat straw burning on Beijing air quality was characterized by significantly increasing fine particulate and CO concentrations, as well as high ratios of PM_{10}/SO_2 and CO/SO_2 [12]. Another study showed a strong association between $PM_{2.5}$ concentrations and the number of fire points in Changchun in northeast China [47].

4.3. Efforts to Improve Straw Utilization from Different Societal Sectors

Long-term, feasible, and sustainable straw utilization at a high rate is a highly complex operation, involving most societal sectors, including agriculture, manufacture, transportation, energy, consumer, finance, and government. There are many initiatives to provide information and technical or financial support to farmers. The following examples demonstrate efforts to improve straw utilization from different societal sectors.

4.3.1. Emerging Business and Marketing Activities

The increasing use of straw as material and fuel calls for business and marketing expertise. There are now brokers in the straw market, with more than 2000 in Anhui province in 2015. More people are expected to enter the industry. End users of straw in Anhui brokers' portfolios include power plants within the province, paper mills in Shandong, and a company in Lianyungang (Jiangsu), where straw is used as edible fungus base. The plan was to expand the market to pellet fuel [48].

4.3.2. Inter-Regional Collaboration

Due to its agricultural origin, straw is often produced in one region but utilized in another. Therefore, inter-regional collaboration is essential. Since 2015, Jiamusi, Heilongjiang has been carrying out a comprehensive straw utilization project in collaboration with a Shandong company. The target annual straw processing capacity is 9 million tonnes within 5 years in three phases. The project was endorsed by the local government [48].

4.3.3. Government Financial Support

Financial support is another key to long-term sustainability of straw utilization. For example, Xingan League (Inner Mongolia) Administrative Committee allocated 50 million Yuan in its 2015 budget to support straw conversion. The construction of 200 pellet straw fuel factories was completed with a processing capacity of 500,000 tonnes of straws per year. The target comprehensive utilization rate is 90% by the year 2020 [49].

4.3.4. Incentives, Responsibility, and Monitoring to Achieve the Utmost Goal of 100% Straw Utilization

Heilongjiang is the number one grain production province in China [50] with the vast majority of operation by large corporations. In 2015, Daxing Farm Corp incorporated comprehensive efforts to implement a plan of 100% in situ straw returning to field [51]. They put into use 36 trail-type straw crushing machines and more than 200 combine-attached straw crushing units. In order to encourage farmers to engage in green agriculture, the Farm subsidized purchasing of straw processing machinery. Monitoring and accountability were employed as well. Inspection teams were established to monitor illegal burning. Furthermore, individual farmers signed liability assurance to abolish burning. This example demonstrates the need for comprehensive measures to encourage farmers to engage in sustainable practices and to take responsibility for their actions.

4.4. The Trend of Straw Production during 1986–2014

Recently, the trend of straw production and utilization in China was analyzed by Ren and Yu [52]. Five major crops were included: rice, wheat, maize, beans, and rapeseed. The annual yield of each of those crops during the period of 1986 to 2015 and the straw-grain ratios [39] were used to estimate annual straw production during the study period and the projected straw production in 2020. Overall, both the national grain and straw productions have been increasing in the past 30 years, with a projected crop straw yield of 545 million tonnes in 2020.

During the same time period, China's farmland is continuously decreasing due to urbanization and conversion of farmland to forest [53]. In 2002 alone, Shanghai turned 5.4 million hectares of cropland to forest [54]. Another reason for dwindling farmland is urban sprawl. In Beijing, the average agricultural acreage had decreased by over 60% from 550,000 hectares during 1986–1999 to 200,000 hectares in 2014 [55]. However, the national-wide grain, as well as straw production, is projected to increase slightly in the near future. The target crop yield is 550 million tonnes in 2020 [56]. The two drivers of the projected increase are, (1) the renewed emphases on self-reliance and food security as the national policy [57] and (2) the rapidly increasing demand for meat [58]. Consequently, the livestock industry is consuming a larger quantity of grain. The increases in grain production per unit area of farmland will be realized through advancements in agriculture science and engineering.

4.5. Analysis of Potential Energy Benefit and Air Emission Reduction

In this section, three scenarios were devised and analyzed to explore the potential energy benefit and air emission reduction in 2020 under different straw utilization rates.

Similar to other parts of the world, China is facing the challenge of meeting an increasing energy demand while minimizing environmental pollution. Thus, using straws as feedstocks for biofuel production is an essential component of the bio-circular economy. Bioenergy projects have experienced rapid development in the past 10 years. As of 2015, 11% of straw was converted to biomass energy [4], including straw liquefaction, straw gasification, solidified power generation, and biochar [59]. The number of households with centralized straw biogas supply had increased significantly from 11,800 in 2009 to 74,900 in 2016 [60]. The annual production of straw-based biochar had reached 287,647 tonnes in 2016 [60]. Renewable Energy Development Plan (2016–2020) of China projected annual biogas (feedstocks, including corn, straws, and other biomass) production of 8 billion cubic meters by 2020 [4].

As seen in Table 1, in all three scenarios, the direct use of straw was set as 69% corresponding to the level reported in 2015 [4]. In the base case, the total utilization rate was 80%, including 11% of straw being converted to biomass energy as in 2015 [4]. The open burning was assumed to be 15%. The resultant air emissions were estimated using emission factors (see Table S2) by Peng et al. [13] and compared with the 2015 anthropogenic emissions from Zheng et al. [61]. As seen in Figure 1, $PM_{2.5}$ and OC emissions were equivalent to 10% each of the 2015 annual national anthropogenic emissions, along with significant emissions of CO (2.6%), BC (2.3%), NMVOC (2.2%), CO_2 (1.1%), NO_X (1.0%), NH_3 (0.47%), and SO_2 (0.28%). The amount of biomass energy wasted due to open burning is equivalent to 60 million tonnes of standard coal (1 tonne of straw = 0.5 tonne of standard coal), in terms of heating value [62], which is 2.2% of the annual national coal consumption of 2.75 billion tonnes [50].

Table 1. Energy benefit of using straw as biofuel instead of open-field burning in 2020.

Scenario	Baseline	Scenario 1	Scenario 2
Percentage of direct straw use	69%	69%	69%
Percentage of straw converted to biomass energy	11%	16%	21%
Percentage of total use	80%	85%	90%
Percentage of open burning	15%	10%	5%
Energy saving compared with baseline			
Amount of straw as biomass energy (million tonnes)		27	55
Equivalent to standard coal (million tonnes)		14	27
Equivalent to standard coal (% of 2015 national assumption)		0.5	1.0

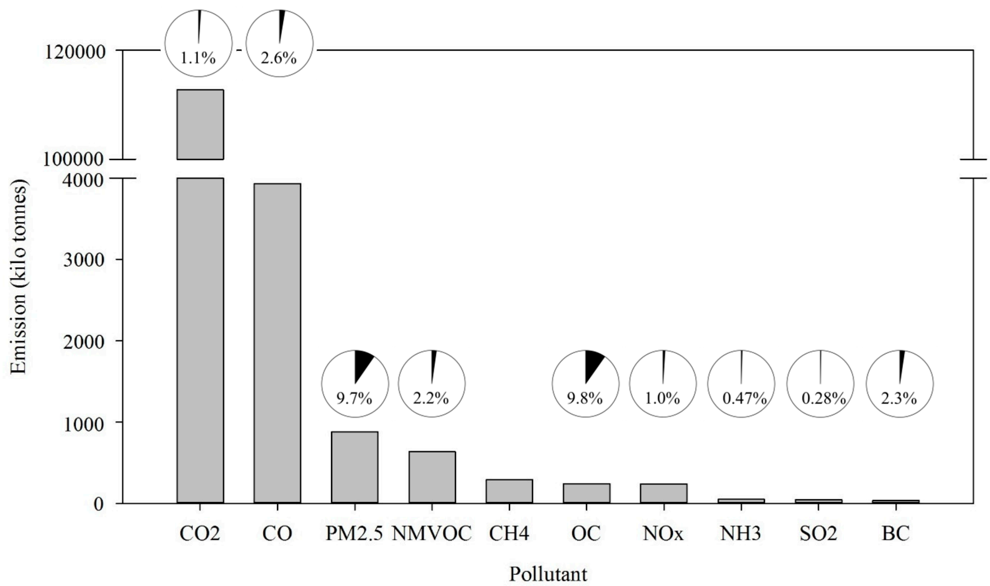

Figure 1. Annual air emissions due to open burning of straws in 2015. Pie charts depict annual straw burning emission equivalent to 2015 annual anthropogenic emissions in China (2015 annual anthropogenic emissions data from [61]. CH_4 anthropogenic emission data not available). CO_2: carbon dioxide; CO: carbon monoxide; $PM_{2.5}$: fine particulate matter; NMVOC: non-methane volatile organic compounds; CH_4: methane; OC: organic carbon; NO_X: nitrogen oxide; NH_3: ammonia; SO_2: sulfur dioxide; BC: black carbon.

Scenarios 1 and 2 represent higher bioenergy conversion rates of 16% and 21%, respectively, thus lower open burning rates (10% and 5%, respectively), pushing the total straw utilization rates to 85%

and 90%, respectively. The energy savings are immense (Table 1), with substantial reductions in air emissions (Table 2).

Table 2. Potential air pollutant emission reductions (kilo tonnes) in China by reducing open-field burning from the baseline (i.e., open-field burning being 15% of national straw production as in 2015).

Scenario	Open Burning	$PM_{2.5}$	BC	OC	SO_2	NOx	CO	NMVOC	NH_3	CH_4	CO_2
1	10%	293.16	11.655	81.375	15.75	79.748	1309.9	211.89	16.485	97.125	37,590
2	5%	586.32	23.31	162.75	31.5	159.50	2619.8	423.78	32.97	194.25	75,180

$PM_{2.5}$: fine particulate matter; BC: black carbon; OC: organic carbon; SO_2: sulfur dioxide; NO_X: nitrogen oxides; CO: carbon monoxide; NMVOC: non-methane volatile organic compounds; NH_3: ammonia; CH_4: methane; CO_2: carbon dioxides.

4.6. Policies and Measures for Straw Utilization in China

The policies and measures for straw utilization in China involve all four levels of governments: national, provincial, county, and township, as shown in Table 3.

Table 3. Chinse governments' involvement in straw utilization policy and implementation.

Level	Law and Regulation	Guidance & Demonstration	Notification	Financial Support	Work Pan	Execution & Inspection
Central government	√	√	√	√		
Provincial government				√	√	
County government				√	√	√
Township government				√	√	√

4.6.1. Laws and Regulations

In China, the central government formulates the laws and regulations applicable to all provinces with the exception of special administrative districts, such as Hong Kong and Macao. For straw burning, the most relevant legislation is *The People's Republic of China Air Pollution Control Act* passed in 2000 [63], in which it stipulates that farmers could be fined RMB 500–2000 Yuan for open-field straw burning. Criminal investigations may be prompted by reports from government offices or concerned citizens. When straw burning causes serious air pollution and/or significant loss of public or private property [64], the penalties are 5–15 days of detention and/or fines of 500–1000 Yuan, depending on the severity of the offense [65]. However, the definition of significant loss is not very clear. Another central government's effort is satellite monitoring of straw burning. Although implemented by the central government, the field inspection, reporting of violation, and reinforcement are being carried out at the county or township levels.

4.6.2. Guidance and Demonstration

The central government also provides guidance. For example, *The List of National Advanced Pollution Control Technologies (the first batch)* introduces comprehensive straw utilization technology in order to promote straw utilization and environmental protection. Those technologies include using straw as briquette fuel, power generation fuel, gasification, and building materials [66]. In 2015, the Information Office of the State Council held a policy meeting on the agricultural, port (for ships), and standardization. It was realized that pollution control in rural areas would pose a challenging and long-term battle. As part of the central government's plan, measures in three aspects will be implemented to reduce pollution: livestock and poultry pollution, plastic seedling film recycling, and straw burning. As pointed out by Shandong Provence Circular Economy Association, utilizing those wastes or byproduct as resources is a sustainable solution to those problems [48].

4.6.3. Notification

The central government issues notifications, mostly during summer and autumn, in order to supervise provincial efforts on banning straw burning. For example, in 2008, MEP issued the *Notification of further Actions on Straw Burning Ban*. Provinces were asked to formulate programs to ban straw burning immediately. It was also announced that (1) satellites will be employed to monitor straw burning and (2) MEP and Ministry of Agriculture will dispatch supervision teams to inspect the provincial programs in May and June of 2008, followed by a nationwide notification summarizing those programs [67].

4.6.4. Financial Support

The central government also provides funds and relevant policies to encourage and support comprehensive straw utilization. An example of policies is that enterprises can claim corporate tax reduction when using straw as fuel to produce electricity or heat [68].

Following the central government's financial support policy, provincial governments formulate funding allocations to counties. Some provinces use the fund to support demonstration zones. For example, Beijing-Tianjin-Hebei and surrounding regions allocated infrastructure funds in 2014–2015 to 10 counties selected as demonstration zones of comprehensive straw utilization [45].

The county governments further allocate the funds to the township level, based on the provincial governments' plans. Yuexi County, Anhui, stipulated numerous subsidies, including 20 Yuan/mu (1mu = 0.067 hectare) for mechanic straw returning to the field, 20–30 Yuan/tonne for purchasing-storage-utilization of straw, 20,000 Yuan for every comprehensive straw utilization demonstration pilot unit (at least 50 mu), and 2000 Yuan for each agricultural machinery [69].

Some county governments set up county-level funds in addition to the funds from the provincial government. For example, Mengcheng County, Anhui, allotted 20 Yuan/mu to each town in 2016 for straw unitization and straw burning ban. Of which, 70% was provided by the provincial government, and 30% by the county [70].

Finally, formulating a detailed subsidy distribution plan is the responsibility of township governments. For example, in 2016, Shidian, Anhui, implemented a plan to ban straw burning and to promote comprehensive straw utilization. A fund of 50,000–200,000 Yuan was provided to each straw collection/storage station with a capacity of at least 500 tonnes. The accompanying straw transportation subsidy was 100 Yuan/tonne. Additional funds were provided for agricultural machineries that return straw to the field [71].

4.6.5. Formulate bans on Straw Burning and Penalty Scheme

Following laws, regulations, and notifications by the central government, it is the responsibility of provincial governments to formulate work plans on banning open-field straw burning and to establish a supervision system. For example, Beijing-Tianjin-Hebei and surrounding regions requested county governments to identify personnel responsible for the enforcement of straw burning bans during 2014–2015. County governments were also requested to carry out inspections at areas surrounding airports, highways, and railway tracks. In addition, the provincial government called for the counties to utilize the media to raise the public awareness of the adverse impacts of straw burning and to expose straw burning incidents [45].

According to the provincial work program, the county government arranges work for each township and formulates penalty schemes imposed. For example, in Yuexi County in 2014, if a straw fire spot of 50 m^2 or larger was detected by satellites, 3000–5000 Yuan of straw related subsidy funds, detailed in Section 4.6.4, were forfeited [69].

4.6.6. Carry out Inspection and Enforcement

The township governments carry out most of the field inspection and penalization tasks related to straw burning. For example, as outlined in *Work Plan of Straw Comprehensive Utilization and Burning Ban in Shidian Township in 2016*, township government staff was asked to patrol day and night during harvest seasons. Once found burning straw, a farmer will be fined 2000 Yuan and the comprehensive agricultural subsidies of that year will be stripped off [71].

4.7. Barriers in Straw Utilization

Nowadays, straw utilization technologies are more mature and practical. There are also numerous policies, plans, and programs at each of the four levels of the Chinese government, including some rather debatable or controversy penalty schemes detailed in Sections 4.6.5 and 4.6.6. However, after its ban nearly two decades ago, widespread open-field straw burning still occurs [13]. The governments, to some extent, appear to be losing the battle. One of the issues is the cost of fines (500–1000 Yuan) and detention (5–15 days) may not be enough to deter the burning practice. Another is the ambiguity of relevant regulations. Both lead to insufficient enforcement and punishment based on existing laws and regulations. Furthermore, the financial support policies follow the hierarchy governmental structure to move downward from the central government to township (see Section 4.6); however, there is a lack of feedback from the lower to higher levels. The needs and challenges of the farmers and the townships are not well considered when developing the funding structure. Moreover, the environmentally friendly alternative of straw utilization depends on an extensive infrastructure of the straw collection, transportation, storage, and utilization at a regional or provincial level, which is largely non-existing now. The development and operation of such infrastructure require a large investment and expertise; both are far beyond the means of individual farmers and townships. Overall, with a high risk of being found guilty, open-field burning remains an inexpensive and readily available option for farmers. Many farmers would rather be fined or detained because they could not afford to miss the plantation nor other options are available.

5. Recommendations

In order to improve the straw utilization rate and reduce air pollution from straw burning, recommendations are made in five aspects as detailed below.

5.1. Finical Support to Users and Producers of Straw Products

In this section, the biomass fuel/stove is used as an example to demonstrate the need for financial assistance to support the infrastructure and activities related to straw utilization.

(1) Subsidies for biomass stoves

Farmers are more likely to purchase biomass stoves with a lower price tag. The lost revenue for the manufacturer could be subject to government subsidies.

(2) Subsidies for straw delivery and straw briquetting factory

For the delivery of the straw to a briquetting factory, farmers should get certain financial subsidy beyond the transportation costs. Straw briquetting factories should distribute the biomass briquette to the farmers at a low price and with high efficiency. This approach requires the government to impose a mandatory field to briquetting factory policy. Furthermore, the government should establish and operate a regional database and logistic system to (1) estimate the straw yield based on the farming acreage and crop types [72] and (2) to monitor and manage the transportation of straw and fuel blocks and the production of the blocks.

5.2. Finical Support to Advance Industrialization of Straw Unitization

Many areas in China are using straw as feed, in cultivating edible fungi, knitting crafts, and in power generation. However, the level of industrialization is low because of its high demand for resources, mostly manpower and capital. For example, the transportation of fresh straw is costly due to its high volume and high density [28]. Therefore, government subsidies in fuel and toll costs could entice enterprises to buy straw from farmers, which will, in turn, speed up the industrialization of straw utilization.

A case study of the Ar Horqin Banner (Inner Mongolia, China) corn straw-based biogas facility analyzed its economic viability. It was found that half of the net profit is attributable to government subsidies, indicating a heavy reliance of this kind of projects on policy support [40].

Furthermore, straw is produced in large quantity and great concentration at the harvest seasons [7]. Anything not processed in situ must be removed quickly. However, most off-site straw processing occurs throughout the year. Therefore, storage infrastructure is required. Government funds should help in the construction of large and medium-sized straw storage stations, with modem technology to ensure continuous supply to factories with decent quality. Another area the government should support is the establishment and operation of quality and price control systems. For example, the moisture content of the straw may determine the price of acquisition [73]. These approaches will help the processing companies to obtain a yearlong supply of materials, which is essential for industrialization of straw utilization. Lastly, ample storage capacity will help farmers to dispose of a large quantity of straw quickly, thus effectively avoiding the occurrence of open-field burning.

It should be noted that if the costs of implementing policies are very high, the costs may exceed the benefits. Policy implementation costs include direct costs, such as infrastructure and subsidies, and indirect costs, including straw burning monitoring and in-kind contribution to monitor and manage collection and transportation of straw and straw-based products. Future studies may need to differentiate between private costs (e.g., to farmers, producers, and consumers) and external costs (to third parties and society). An unfavorable private cost-benefit-ratio may hinder the implementation of certain projects. However, by including external cost and benefits (e.g., from reducing air pollution and GHG emissions) in cost-benefit analysis, a greater number of straw utilization options might become desirable from a societal perspective. Such analysis will also justify long-term policy support for those options.

Moreover, subsidies for the bioenergy sector may result in diverting straw resources away from more competitive uses or even more ecologically beneficial ones. Therefore, further expansion of biomass energy production should be carefully evaluated, taking into consideration (1) the need of increasing straw returned to field, thus to improve soil quality, ensure sustainable crop yield, and reduce erosion [38], (2) the competing need of other usages, for example, animal feed, building materials, and cultivation of edible fungi [4], and (3) the practical and economic constraints in straw collection and application toward energy production.

5.3. Voluntary Carbon Trading

The use of straw as materials or fuels reduces emissions of greenhouse gases and other air pollutants [7]. Users of straws as biofuel and materials, including companies, governmental sectors, non-governmental organizations, and individuals should be awarded by various forms of compensation for their reduced emission of greenhouse gases [74]. One example is that biomass stoves in the rural household could be developed as a CO_2 emission reduction/climate change mitigation project, and trade on the voluntary carbon market. The resultant carbon credits could be used to continuously subsidize the manufactories and users of the biomass stove. The administrative burden is a significant barrier for individuals to participate in emission trading. However, large regional programs are more likely to be successful. With the assistance of Chinese Rural Energy Association and Beijing Chemical Engineering University, a biomass stove program by Shanxi Jinqilin Energy Technology Co. LTD was recognized as a Clean Development Mechanism (CDM) project. In June 2011, that project was certified by the United Nation as the first biomass stove carbon trading project in China and the third one in the world at that time. The initial trading quote was 49,308 tonnes of CO_2 equivalent, valued at 493,080 USD with 60% of the revenue allocated to further promoting biomass stoves in the region. By the end of 2012, the fund had subsidized 3577 stoves [75].

At the beginning of 2019, national carbon trading is still under development in China. However, there have been a few regions, including Beijing, Tianjin, and Shanghai, where the carbon trading scheme has been piloted since 2011 [76]. We recommend a pilot project being carried out in the Beijing-Tianjin-Hebei region, to set a quota for the voluntary carbon trade, and to give priority to clean stoves and biofuels, including straw briquette. The reasons are (1) Straw yield in Hebei ranked fifth in China in 2014, and (2) Hebei is adjacent to Beijing and Tianjin, therefore could take advantages of mature carbon trading platforms in those two large cities.

5.4. Prescribed Burning—An Interim Solution

Considering the technical, financial, and logistical difficulties in comprehensive straw utilization analyzed in previous sections, we recommend prescribed burning as a viable short-term solution in some areas of China, where the removal of straw possess a heavy burden on the farmers. Prescribed burning, also known as controlled or planned burns, is the planned and controlled application of fire to a predetermined land area. It is an effective and efficient means for resources management [47,77]. Studies have shown that farmers often burn straws right before the effective date of burning bans or a major snowstorm (e.g., [47]). Consequently, widespread burning of the open-field in a day or two hammers the air quality greatly. Furthermore, a survey in Thailand found that two-thirds of farmers burned residues in the afternoon [77] when dry and windy conditions support a faster and more complete burning. Unfortunately, those meteorological conditions also favor the dispersion of air pollutants.

Adaptation of prescribed burning in agriculture residue management could result in far less impact on air quality in urban centers by allowing farmers to burn the straws during a longer time period when the weather conditions are less contusive to atmospheric mixing and regional transport. This requires incorporation of weather and air quality forecast, including wind speed, air mass directions, temperature, relative humidity, and precipitation [47,77]. Based on this information, prescribed burning could be allotted in some areas (e.g., downwind of a big city) for a specific time period (e.g., a few days), then move on to other areas to ensure on-time completion of burning in the region.

5.5. Effective Education, Incentive, and Enforcement Frameworks

Few program or policy would be successful if it positions the government against the farmers. An education program should be devised to promote the economic and environmental benefits of straw utilization, such as clean biomass stoves, and provide resources to direct farmers to have assistance on financial and technical issues. The goal is to make farmers realize that the government is helping them in the transformation to green farming, clean energy, and a healthy and environmentally friendly lifestyle in rural areas. On the other hand, the effectiveness of a particular program/policy may differ among different regions. Instead of using the same program year after year or adopting programs from other places without careful evaluation, each region should reflect on the success and failure of past programs locally and in other areas on a regular basis.

Education programs alone are inadequate to achieve a radical reduction in straw burning. A reporting system of straw burning should be devised using various sources, including unmanned aerial vehicle and satellite images. Furthermore, each violation should be investigated, and the enforcement of laws and regulations should be monitored. In addition to effective incentive mechanisms, some voluntary agreements are also likely to be endorsed by farmers. Lastly, local governments should be held accountable in reducing straw burning and in increasing the use of straw.

6. Conclusions and Policy Implications

Being the world's largest grain producer, China's annual straw yield was 700 million tonnes in 2014, which poses great challenges and opportunities in comprehensive straw utilization. It is possible to meet these challenges as there are case studies of success from all over the world. Research, development and implementation outcomes in different countries suggest that technology advancement is only one of many determinants for the viability and long-term sustainability of straw utilization. Other key factors include careful feasibility evaluation, availability of infrastructure and logistics, business and marketing expertise, inter-regional collaboration, comprehensive and adaptive policies, and long-term support from the government.

In China, the straw utilization rate was 80% in 2015, much higher than in some developing countries. However, the rate varied greatly among different regions within the country. Overall, both the national grain and straw productions have been increasing in the past 30 years, with a projected crop straw yield of 545 million tonnes in 2020. China has the potential to realize significantly reduced coal use, accompanied by a reduction of 75 million tonnes of CO_2 emissions, if the conversion of total straw yield into bioenergy can increase to 21% (from 11% in 2015).

Through an in-depth analysis of the current status of relevant laws, regulations, policies, and management practices, it was found that the current efforts in China rely heavily on prohibition and penalties, and fall short on effective preventive measures and viable alternatives. This is the primary cause of the seemingly widespread violation of straw burning bans. Major obstacles in comprehensive straw utilization include a lack of adequate and long-term government financial support, a lack of feedback mechanism to reflect the needs of farmers, and a lack of infrastructure and logistics to support the highly complex operation of straw collection, transportation, storage, utilization, and marketing of the products, all those involve most societal sectors, many people, and facilities often in different regions. The authors believe that regional and national efforts to overcome these identified major barriers are essential to increase straw utilization and to drastically reduce open-field burning. Recommendations were made to promote a bio-circular economy around using crop straw as resources, including increasing government support in building infrastructure for straw storage and processing, exploring the carbon trading market to entice straw utilization, implementing prescribed burning as a transition approach toward the eradication of open-field burning, and enhancing education, incentive, and prevention mechanisms. Overall, there is an urgent need to shift from the current administrative, short-term, fragmented, prohibition, and penalty based policies to policies that are long-term, cohesive, stable, economically effective, results-oriented, and backed up by the legal systems.

With the increasing demand for food and energy, energy conservation and environmental protection are gaining attention worldwide. It is well-known that straw utilization leads to energy savings and air emission reductions in comparison with open-field burning, which is an important step toward the circular economy. Most issues discussed in this review are not unique to any jurisdictions. Countries with large straw yields or those considering improving straw utilization may benefit from the analysis methods and/or results provided here.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/6/1762/s1, Table S1: N, P_2O_5, and K_2O contents (% of dry matter) in wheat straw, corn stalks, and soybean straw. Table S2: Emission factors (g/kg) of five types of straw.

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