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Review

Management of Crop Residues for Improving Input Use Efficiency and Agricultural Sustainability

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Received: 5 November 2020; Accepted: 21 November 2020; Published: 24 November 2020

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Abstract: Crop residues, the byproduct of crop production, are valuable natural resources that can be managed to maximize different input use efficiencies. Crop residue management is a well-known and widely accepted practice, and is a key component of conservation agriculture. The rapid shift from conventional agriculture to input-intensive modern agricultural practices often leads to an increase in the production of crop residues. Growing more food for an ever-increasing population brings the chance of fast residue generation. Ecosystem services from crop residues improve soil health status and supplement necessary elements in plants. However, this is just one side of the shield. Indecorous crop residue management, including in-situ residue burning, often causes serious environmental hazards. This happens to be one of the most serious environmental hazard issues witnessed by the agricultural sector. Moreover, improper management of these residues often restrains them from imparting their beneficial effects. In this paper, we have reviewed all recent findings to understand and summarize the different aspects of crop residue management, like the impact of the residues on crop and soil health, natural resource recycling, and strategies related to residue retention in farming systems, which are linked to the environment and ecology. This comprehensive review paper may be helpful for different stakeholders to formulate suitable residue management techniques that will fit well under existing farming system practices without compromising the systems' productivity and environmental sustainability.

Keywords: residue management; soil degradation; GHGs; resource use efficiency

1. Introduction

Agriculture and associated sectors, which are the mainstay of economies in many developing and undeveloped countries, covering almost 82% of the world's population directly or indirectly, need to be sustainable for bringing about greater prosperity of human beings. This requires the introduction, adoption, and development of improved production technologies [1]. The technologies conserving resources in agriculture are the most valuable keys to ensure sustainability in food production. The adoption of such input-intensive agricultural practices often leads to serious depletion of soil nutrients. The use of modern heavy farm implements like the combine harvester, rotavator, and seed cum fertilizer drill is increasing day by day. The use of the seed cum fertilizer drill and combine harvester in the rice–wheat system of the Indian subcontinent has increased manyfold in the last few years [2,3]. The production of crop residue in modern input-intensive agricultural practices was also linearly increased. Farmers often burn these crop residues in-situ, which leads to serious environmental impacts [4–6]. Burning of crop residues has a serious negative impact on human health as well as environmental consequences. It was reported that in-situ crop residue burning in Asian countries accounted for more than one-third of total biomass burning [5]. The particulates (PM) released from such burning, like PM10, PM2.5, and greenhouse gases (GHGs), are also responsible for environmental pollution [5,7].

Crop residue management is a well-known and widely accepted practice for controlling various soil physical, chemical, and biological functions. Crop residues incorporate a large number of nutrients in the soil for crop production and affect soil water movement, runoff, and infiltration. In a conservation agriculture (CA) system, successful management of crop residues is an integral part, and the maximum benefit of CA can only be achieved with in-situ management [8]. However, decomposition of crop residues has both positive and negative impacts on crop production. The role of the researcher is central in employing the positive effects of crop residue management practices and improving positive impact on the environment [9]. Soil management with crop residues covers a wide range of aspects, like residue decomposition, soil erosion control, nutrient recycling and availability to plants, control of weed pests, and various conservation practices related to tillage for maximizing crop yields [10]. The annual cycling of plant nutrients is important in the plant–soil ecosystem in order to maintain a productive agricultural system and to facilitate better nutrient mobilization within the system [11]. It is reported that soil, air, and water, which have tremendous interaction with plants, release various essential inorganic nutrient elements for plant growth [7]. Apart from this, carbon-enriched crop residues serve as the main food source for soil microorganisms and initiate the biological nutrient cycling framework. Throughout microbial decomposition of crop residues, different chemicals are released in soil and can be properly utilized by plants and other living organisms [2]. Plant availability of NPK nutrients from crop residues mostly depends on different soil physical, chemical, and biological processes. Integrated management with fertilization and the amount of crop residue remaining for incorporation in the crop field determine the degree of cycling and plant availability of nutrients from crop residues. Management of crop residues for a better C sequestration and the amount and site of crop residue application coupled with optimum use of N fertilizer are necessary for promoting soil organic matter [12,13].

In the present review, we have focused on the different aspects of crop residue management, like the impacts of residues, utilization of natural resources, and strategies to be formulated for better residue management in farming systems, which are largely related to the present-day environmental issues. Efficient crop residue management strategies for sustainable crop residue management without compromising the crop yield must be framed for maximizing the input use efficiency for food and environmental security.

2. Intensive Agriculture and Crop Residues: Present Status

The modern intensive agricultural system depends on the heavy application of external inputs. Farmers who practice such modern input-intensive agricultural practices usually follow intensive crop rotation practices, and the lands remain fallow during a crop season in a cropping year [14]. The adoption of intensive agricultural practices coupled with high-yielding varieties and modern irrigation facilities often leads to micronutrient deficiencies and decreased soil fertility. It has been reported that a steady shift from the use of different organic manures and traditional plant nutrient elements (farmyard manure, composts, etc.) instead of chemical fertilizers is considered as a most promising technique to resolve this problem [15]. In addition, these modern intensive agricultural practices often cause severe undermining of micronutrient reservoirs in soil, resulting in their deficiencies in many areas across the country.

Crop residue management usually refers to maintaining the soil surface cover and protecting the soil from nutrient losses as well as erosion. In addition, it helps in improving different physical, chemical, and biological processes within soil [16]. It protects soil from wind and rain erosion, conserves soil moisture, and improves infiltration and aeration within the soil profile. Proper crop residue management helps in adding soil organic matter and provides food for soil micro-organisms [17]. Soil, water, air, and sunlight are considered to be the major resources that sustain food supply and maintain global ecosystems. Crop production is the utmost manipulation of these natural resources, especially the soil [18]. Quality soil, enriched with organic matter, boosts crop production. Incorporation of crop residues improves soil organic matter [19]. After harvesting the economic parts of field crops, residues, i.e., stem, leaves, husks, etc., play decisive roles in improving soil quality as well as addressing several environmental issues. These crop residues generally act as a primary contributor to elemental carbon in soil [20]. Crop residues are usually considered as waste material in terms of their economic importance. However, crop residues offer a variety of potential mechanisms for nutrient recycling, especially carbon sequestration in soil [21]. A report on crop residues by the Ministry of New and Renewable Energy reported that India produces 500 Mt (million tons) of crop residues (Figure 1) every year [22]. A big share of residues are used for domestic as well as industrial purposes. Apart from those, a huge portion is retained in the field and burned every year, as recorded in different research articles. It is also interesting that the residue portion burned in India as waste material is approximately the amount of crop residues jointly produced by other countries in the same region.

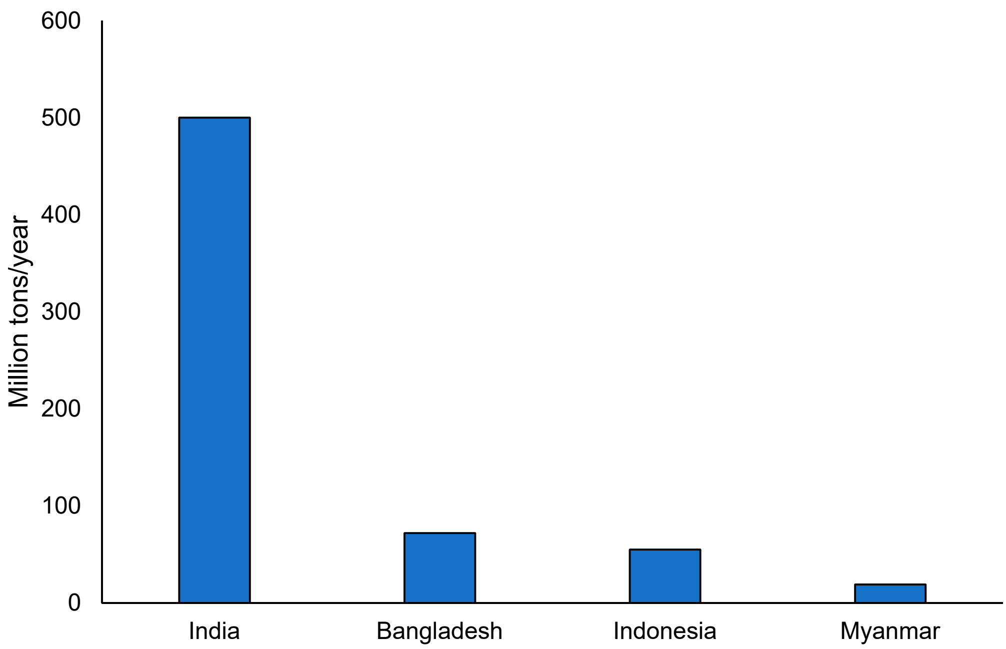

Figure 1. Agricultural waste generation in India compared to other select nations (source: modified from National Policy for Management of Crop Residues (NPMCR) [22]).

3. Environmental Impacts from Inefficient Use of Crop Residues

Modern intensive agricultural practices rely on the high-yielding and hybrid cultivars of food crops, and very often, these cultivars require a large dose of modern synthetic inputs like chemical fertilizers and pesticides [23]. However, the impact of indiscriminate use of these chemical inputs without considering the future and negative impacts on the environment is starting to show up, and yields of crops have flattened despite using larger doses of fertilizers. Environmental pollution is occurring at an alarming rate. With the increasing cost of cultivation in conventional agricultural practices and no appreciable additional benefits in income, farmers are finding it extremely difficult to earn their livelihood. The situation would further deteriorate with gradual fragmentation of holdings. To improve the socioeconomic standards of the farmers in the modern day and to produce crops at a lower cost with improved crop productivity and soil health, it is essential to shift the modern farming practices to conservation agriculture for sustainable growth [24]. Intensive agricultural practices often aggravate soil and water erosion and make the system a vulnerable one, leading to degradation of precious natural resources. On-site burning of crop residues usually results in of CH_4 and N_2O gases produced by the ignition of crop residues and the emission of GHGs from agricultural crop residue burning. Amongst the different crops, globally, maize contributes the highest emissions (CO_2 equivalent—gigagram) through burning of crop residues, followed by rice, wheat, and sugarcane (Figure 2). Amongst the different countries, the highest GHG emissions (CO_2 equivalent—gigagram) through the burning of crop residues were emitted by China, followed by India, the USA, and the USSR (Figure 3).

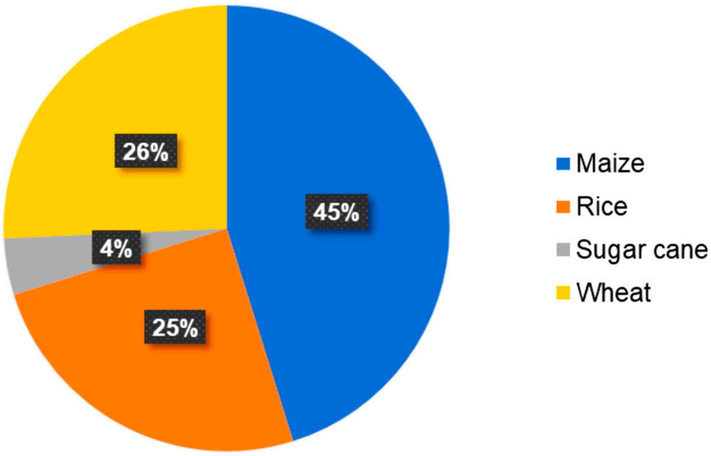

Figure 2. Emissions (CO_2 equivalent—gigagram) from the burning of crop residues (source: Food and Agriculture Organization (FAO)) [25]).

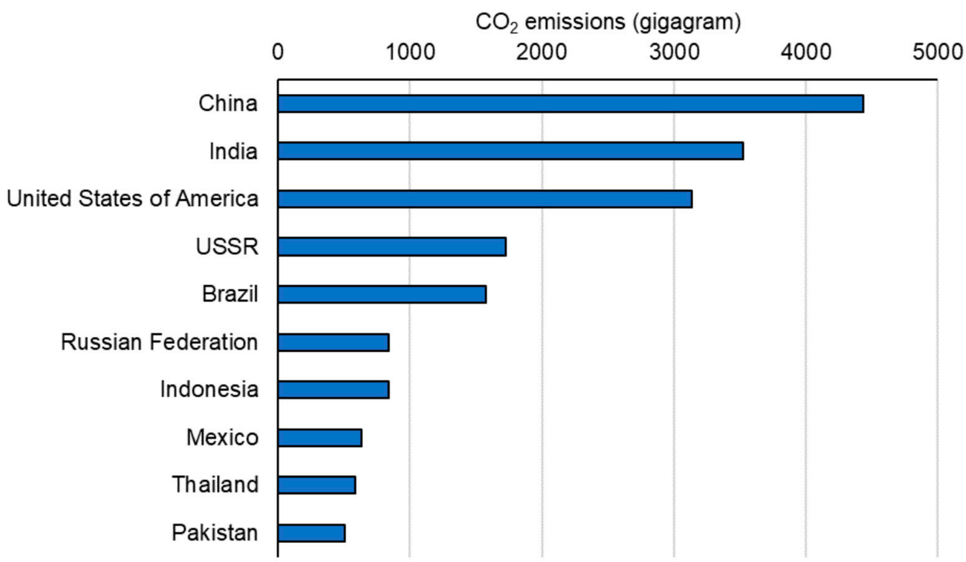

Figure 3. Top 10 emitting (CO_2 equivalent—gigagram) countries according to burning of crop residues (source: Food and Agriculture Organization (FAO)) [25]).

Crop residues offer multiple environmental services when retained in field conditions after harvest. A list of contributions has been recorded in different research articles; e.g., improving soil physical properties and contributing to soil organic carbon (SOC) formation [11–13]. Very often, crop residues are considered as waste materials, but they perform as a valuable resource when returned to the soil, and they deliver numerous ecosystem services to the environment [4]. In addition, crop residues often reduce the dependency on fossil fuels and include a positive impact on the environment [10]. In addition, the World Energy Council has reported other utilities of crop residues for domestic (cattle feed purpose) and industrial purposes [26]. Due to a rise in population and growing demand for food, crop production followed by management of crop residues has been increased globally.

The large contribution of crop residues as a natural resource for developing soil stability and soil fertility is portrayed in different research articles. In addition, good management practices for crop residues increase irrigation efficiency and control soil erosion to a large extent. However, the large-scale implications of management practices with crop residues limit their use due to intensive cultivation practices in many areas across the globe.

4. Management of Crop Residues for Improving Input Use Efficiencies

The implementation of sustainable crop residue management practices is one of the cleaner crop production options [27]. Indiscriminate burning of the crop residues has a serious impact on soil health, organic matter content, and plant micro- and macronutrients, as well as on microbial population [27,28]. Sustainable management of crop residues to lessen the ill impact on the environment as well as on human beings is a serious challenge for scientists and policymakers. Farmers are often reluctant to adopt any remedial measures for sensible management of crop residues because these practices do not directly increase the farm income. So, the selection of suitable crop residue management strategies that are eco-friendly but also increase the farm income is of the utmost importance. In practical field conditions, numbers of potential crop residue management technologies like conservation tillage, cycling of nutrients, soil conversation practices, zero-tillage and residue mulching, use in animal feed, and preparation of vermicompost are being used in different parts of the world [27,29–33]. Proper crop residue management has a positive impact on improving input use efficiencies by regulating different soil biochemical properties.

4.1. Improving Soil Physical Properties

Incorporation of leguminous crop resides has been shown to improve the soil physical properties, such as water-holding capacity, soil permeability, etc. Inclusion of leguminous crop residues also increases crop growth and productivity by enhancing the availability of nutrients for the root zone of the crops [34]. Use of heavy machinery and farm implements like planters, zero-tillage implements, reapers, and combine harvesters is very common in modern input-intensive agriculture, and indiscriminate use of these heavy pieces of machinery often leads to compacting the soil and hampering the soil physical properties, like infiltration rate, airflow, and water-holding capacity [35]. Carlesso et al. [35] reported that the application of crop residues obtained from ryegrass and straw residues as well as mixed litter can significantly improve the soil porosity and water-holding capacity, and can ultimately make the soil more productive. Application of crop residues along with conservation tillage was reported to improve the soil aggregate and carbon storage in rice-based cropping systems [36].

4.2. Improving Soil Chemical Properties

Sustainable management of crop resides can efficiently improve the soil chemical properties, like pH, electrical conductivity, and cation exchange capacity (CEC), as well as the transformation of different primary and secondary plant nutrients. The soil carbon pool (both total and labile pool) has a positive correlation with the application of crop residue. It is reported that application of wheat residue mulching at a rate of 10 Mg ha^{-1} along with the application of 75 kg N ha^{-1} can significantly increase the total and labile carbon pool of an irrigated maize production system [37]. Adoption of conservation tillage in a rice-maize cropping system with residue management can be effective for improvement of system productivity, K use efficiency, and apparent K balance [38]. Residue incorporation is also helpful for recycling of soil available K by up to 15%, as well as, thereby, the demand for external supply of K [38]. Smitha et al. [34] reported that application of cluster bean crop residue before transplanting of sacred basil (*Ocimum sanctum* Linn) significantly improved the SOC and availability of soil macronutrients.

4.3. Improving Soil Microbial Activity

It has been reported that proper retention of crop residues has a significant impact on the regulation of the soil microbial biomass. The enhanced microbial activity in the top layer of soil by application of crop residue mulching was reported by Samui et al. [39] and Mondal et al. [3], and these might be due to the alteration of plant–soil micro-climate, increased water and nutrient availability, and regulation of soil temperature. Comparable findings were observed by Chatterjee et al. [37], and they opined that soil microbial biomass carbon (MBC) significantly increased through application of wheat crop residue. Incorporation of residues of leguminous crops like cluster bean before sowing the next crop was reported to increase the soil microbial biomass and dehydrogenase activity (DHA) as compared to the control (with the application of crop residue) treatment [34]. Residue retention under CA has also been reported as beneficial for the reduction of soil nematode population in a wheat–soybean cropping system [40].

4.4. Improving Soil Productivity

Judicious crop residue management is very helpful for maintaining the soil productivity and recycling of soil nutrients [41]. Rusinamhodzi et al. [41] reported that successful management of crop residue was not only beneficial for the improvement of soil productivity and nutritional status, but also helps to improve the overall health status of the farm animals. Long-term application of crop residues along with conservation tillage was reported to boost the soil productivity, C-pool, and earthworm population [42,43].

5. Crop Residues Improve the Fertility and Productivity of Soil

Soil fertility is the inherent capacity of soil to sustain a satisfactory supply of nutrients for plants, and can be determined through chemical analysis of soil. However, soil productivity is the integrated result of soil fertility and management factors in field conditions, and can be assessed from crop yield. Soil fertility is well connected with the soil physical, chemical, and biological properties naturally linked with soil organic matter stock. Recently, more emphasis has been given to healthy food production, maintaining long-term soil fertility, and environmental sustainability, along with natural resource conservation and more productivity through appropriate soil and land management, residue recycling, precision technology, and the supply of plant nutrients more from organic sources instead of inorganic chemicals [44].

Crop residue is gaining importance in global agriculture, and is considered as an excellent source of organic matter that helps to improve C stock in soil, as well as water conservation, nutrient recycling, and soil qualities, and decreases the trends of residue burning and the consequent environmental hazards upon retention (Figure 4) [45]. Most of the total amount of crop residue production comes from cereals (74%), followed by sugar crops (10%), legumes (8%), tubers (5%), and oilseeds (3%) [12]. In addition to C, crop residue contains several mineral nutrients depending on the crop species and soil fertility status [12]. However, it is very difficult to determine how many nutrients will be available to the crops at the time of crop residue incorporation, as it has been well established that, initially, crop residues immobilize the available soil N as a consequence of the high C:N ratio [46]. However, in the long term, this practice is very effective for nutrient availability for subsequent crops along with high-quality organic matter generation, and it facilitates better food crop production [10]. The cultivation of legumes generates the most residues after cereals [47]. Rather than quantity, residues from legumes are considered as good-quality residues, and contribute an extensive amount of soil C for a long duration [48]. A comprehensive assessment of crop residue application in agricultural practices concerning soil fertility and productivity is discussed below:

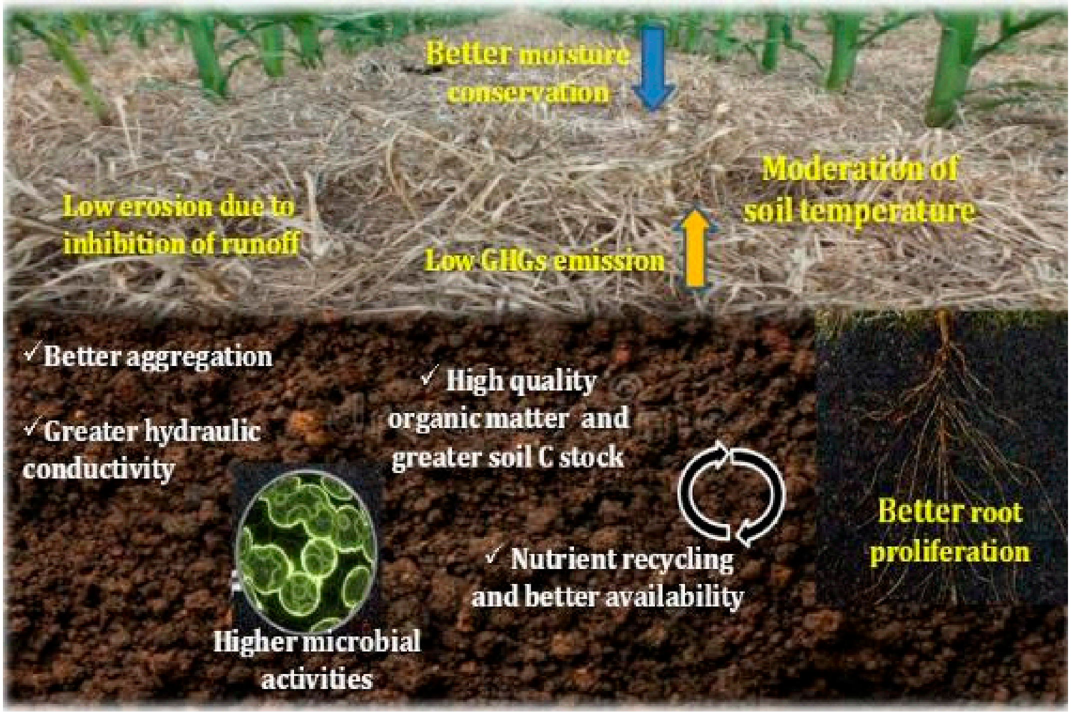

Figure 4. Advantages of crop residue retention for improving soil fertility.

5.1. Crop Residue Management for Soil Organic Matter

Incorporation of crop residues into soil significantly changes the labile pool of soil organic matter [49]. It is reported that continuous residue incorporation for three years significantly increases the light carbon fraction in the soil, which has a great contribution to total soil organic carbon [50]. In long-term practices, the changes in total organic carbon are the result of changes in heavy-fraction carbon (>1.6 g cm^{-3}) depending on residue management practices [49]. Intensive agricultural practices facilitate the continuous loss of organic matter, with its detrimental effect on global carbon balance and soil quality. The legume-based residue incorporation ensures huge biomass production and confirms the net gain of soil carbon as compared to cereals [51]. Legume stubbles contain 49% higher carbon and 133% higher N, and they add 60% more SOC compared to control plots (no residue incorporation) beyond 30 cm soil depth. However, the green manuring of legumes has a small impact on soil C storage due to the narrow C:N ratio (12–13:1) and the lower lignin content (49); this is one of the reasons for the quick decomposition of the residues. Residue retention of sunn hemp resulted in 0.92% more SOC and 0.64% less soil inorganic carbon (SIC) compared to control plots (no residue incorporation) [49]. The ability to capture atmospheric N and subsequently store it in the soil would have resulted in a low C:N ratio in its residue, accelerating the N availability, which is required for rapid residue conversion from a C pool into a particulate C fraction. This change in soil organic C content varies with different regions due to the variations of edaphic and climatic factors, as well as the residue management practices. For example, approximately one or two decades are required to move the soil C content to a new equilibrium with good residue management in Europe and America, whereas in Australia and Asia, about two decades are required to reach the soil C level [10].

5.2. Effects of Crop Residues on Soil Nutrient Status and Its Availability

The nutrient content in crop residues is not readily available to plants initially after incorporation, as they are organically bound and need to be mineralized to turn into the available form [52]. After incorporation, a range of soil microorganisms colonize the residues, and decomposition and subsequent mineralization take place; thereby, the crop residues are converted into simple monomers that are further physically, chemically, and biologically assimilated and, ultimately, converted into organic matter [53]. Moreover, some nutrients in crop residues are present in the soluble inorganic form, such as K^+ and SO_4^{2-}, or are associated with mineralizable organic constituents, e.g., protein-bound S or phosphate ester [52]. The advantage of crop residue incorporation is that the soil microorganisms temporarily immobilize the nutrients that are released into the soil from residues and conserve the nutrients as slowly available forms; therefore, plants cannot take up all of the nutrients at one time, but the nutrients may become available throughout the crop's life or in the subsequent crop. This accelerates the nutrient use efficiency and prevents nutrient losses through leaching or volatilization. The remarkable increase in nutrient use efficiency because of residue retention was observed by Pituello et al. [54] and Piccoli et al. [55].

The nutrient distribution is significantly increased by repeated residue decomposition, and previous researchers established the greater organic and inorganic phosphorus accumulation in the soil surface with the practice of conservation tillage compared to conventional tillage [56]. It has been predicted that higher organic matter accumulation in conservation practice may enhance the P content in available form by saturating P adsorption sites on soil colloids. A similar result was also observed in the case of N availability [57].

A significant difference is observed regarding soil nutrient losses when crop residues are left on the soil surface as compared to clean tillage practices. Additionally, they moderate soil temperature, water content, and infiltration rate [58]. Residues retained in soil surface minimize the soil erosion and thus reduce the surface nutrient losses [12]. In contrast, residues with a high decomposition rate may increase the N losses through leaching and denitrification, or sometimes through heavy uptake of N by weeds. A high level of total K is in residues; thereby, residue removal from fields increases the chance of K deficiency in soil [59]. Interestingly, the organic structure of plant tissues does not contain K; thus, the release of K does not depend on residue decomposition. Rainwater or irrigation may wash out the K from the residues, and if there is no crop demand, this nutrient may be lost from the soil differently. This reflects the importance of residue management with consideration of the time of nutrient release and crop demand.

The decomposition and release of nutrients depend on the crop residue quality, especially the presence of N, lignin, and polyphenol, and may influence the dynamics of decomposition [59]. The residues generated from legume crops have a high level of N in the leaves and facilitate rapid mineralization, while crop residues from cereals with high C:N ratios may necessitate extra nitrogenous fertilizer to mitigate the demand for microbial N for decomposition [49].

5.3. Effects of Crop Residues on Soil Productivity

Soil productivity is the comprehensive result of soil fertility and agronomic management, and it is determined by calculating the yield from the unit area. The influence of crop resides on yield is related with overall fertility dimensions, such as soil physical, chemical, and biological properties [60]. Previously, it has been well documented that crop yield always positively correlates with soil organic matter content [61] and residue retention brings up soil organic matter storage. Crop residues mostly influence the productivity in cereals compared to other crops [62]. It has been predicted that more residues add additional soil C and improve the soil properties in terms of favorable temperature, water retention, microbial activities, and nutrient mobilization [63]. Piccoli et al. [55] established that, as a source of organic matter, incorporation of crop residues resulted in 12% and 16% higher yield in maize and sugar beet, respectively, than other sources. However, Hijbeek et al. [61] observed a maize yield increase of only 4% with residue retention. Furthermore, Mandal et al. [64] observed a 12.3% yield increase in wheat when straw was left over on the field. Long-term rice residue incorporation (13 years) resulted in 53.25% and 34.89% higher yield in wheat as compared to residue removal and residue burning, respectively. They also reported a similar trend in the case of maize, and concluded that overall soil physical, chemical, and biological properties, particularly the increase in the soil organic matter, improved significantly. Improved C stock and microbial activities were major reasons behind this greater soil productivity.

6. Crop Residue Management Decreases Soil Degradation

It is estimated that, on average, commonly grown tropical crops like rice, wheat, maize, etc. contain 40% C, 0.8% N, 0.1% P, and 1.3% K, and provide food and shelter for beneficial soil microbes [65]. In addition, removal of crop residues for cattle feed or other industrial purposes increases nutrient removal from croplands and harms soil with multiple adverse impacts, ranging from erosion and degradation of soil to hampering soil, air, and water quality. Thus, the leftovers of crop residues after a harvest can successfully conserve the resources in the soil and sustain the productivity.

6.1. Erosion

Efficient utilization of residues is reported to reduce runoff, sediment transport or losses, and water conservation [65]. It is reported that application of residue mulching can reduce the extent of soil loss by up to 43 times as compared to bared land. Mulching also helps to reduce the runoff, nutrient loss, and sediment present in the runoff water. It has also been reported that a maximum ground cover with crop residue can reduce the topsoil losses to an extent of 30%. Legumes are the most potent option as a cover crop, as they add atmospheric nitrogen symbiotically and, thus, they can improve the soil health. Application of crop residues affects runoff and sediment transport and conserves water. As plant density and residue mulching increase, the potential for runoff decreases [66]. Soil erosion and removal of the top fertile layer of soil largely depend upon the selection of the cropping system. Monocropping with erosion-permitting crops accelerated soil and water loss year after year. In an experiment [67], it was reported that retention of soybean residue can reduce the soil loss by 50% as compared to soil with no residue retention. Conservation tillage and crop residue management are also reported to be effective against soil loss in wheat-based cropping systems in Ethiopia [65].

6.2. Salinity

While experimenting to judge the effect of straw mulching on zero-tillage potato in the coastal saline zone of West Bengal, India, Brahmachari et al. [32] reported that salinity development in rice-fallow fields was significantly faster than in a zero-tilled–mulched field (Figure 5). Surface mulching shows an important and positive impact on the control of soil salinity through reduction of evapotranspiration. Fan et al. [68] reported that the soil salinity level (0.44%) was decreased to 0.07% after straw mulching for two years. Yang et al. [69] also reported that, in the mulched condition, the salinity level in the soil surface layer was lower compared to the control conditions (no mulch).

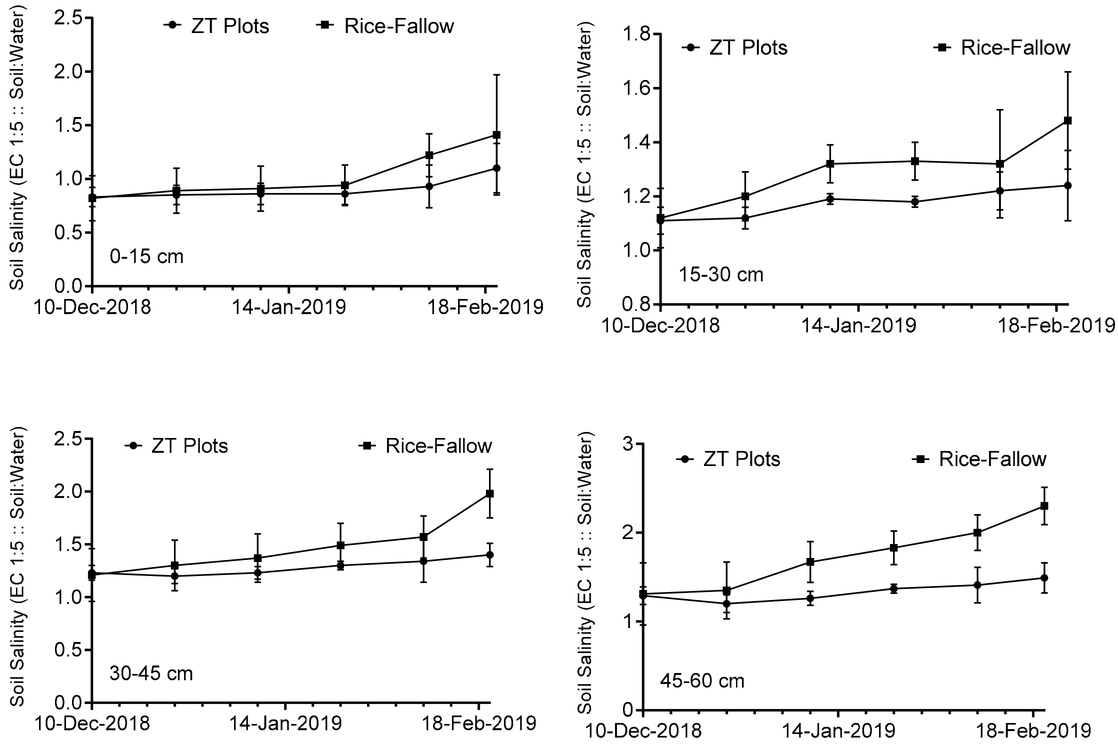

Figure 5. Comparison of soil salinity between zero-tilled–mulched potato fields (ZT Plots) and adjacent rice-fallow fields (rice-fallow) (vertical bars indicate the standard deviation of the mean) (source: modified from Brahmachari et al. [32]).

6.3. Buffering Capacity

Soil buffering capacity, or the cation exchange capacity (CEC) of the soil, is to keep the base-forming cations available for exchange with the soil solution [67]. The CEC is often considered as an effective indicator of soil fertility. As soil organic matter (SOM) content is directly proportional to the soil residue incorporation, soil pH-dependent CEC also increases with the residue retention. In a long-term study, Govaerts et al. [70] reported that continuous incorporation of crop residue might be effective for increasing the CEC of the topsoil layer.

6.4. Decrease in Soil Aridity

Soil moisture is considered as the key element that governs nutrient availability, crop growth, and development. Surface residue retention is very beneficial for rainfed and dryland areas due to its ability to conserve the soil moisture. Residue mulching is considered as an efficient method of manipulating the crop-growing environment for boosting crop yield and improving the quality of the product by controlling soil temperature, retaining soil moisture, and reducing soil evaporation [32,71]. Increased mulch coverage reduces splash erosion significantly with increasing ground coverage. Generally, the mulching treatments store higher soil moisture compared to the untreated soil (bare soil) [72,73]. In an experiment conducted in the coastal saline zone of west Bengal with zero-tillage straw mulching technology for potato cultivation, Brahmachari et al. [32] reported that the periodic moisture depletion from the mulched field was significantly slower than that of bare rice-fallow land. On the other hand, reduction in soil moisture was more significant in the top layer of soil (0–30 cm) than in the deeper soil layer (Figure 6). Zero-tillage and mulching act as a barrier to diminish the evaporation from the top layer of soil by reducing the capillary rise of soil water [39]. Brahmachari et al. [32] recommended that the present zero-tillage mulching technology for potato cultivation was very beneficial for the coastal saline zone to retain soil moisture in the dry winter months. In the dry tract, where rainfall is far lower than the mean evaporation, surface residue retention is a potential option for conservation of soil moisture by reducing the capillary loss [14].

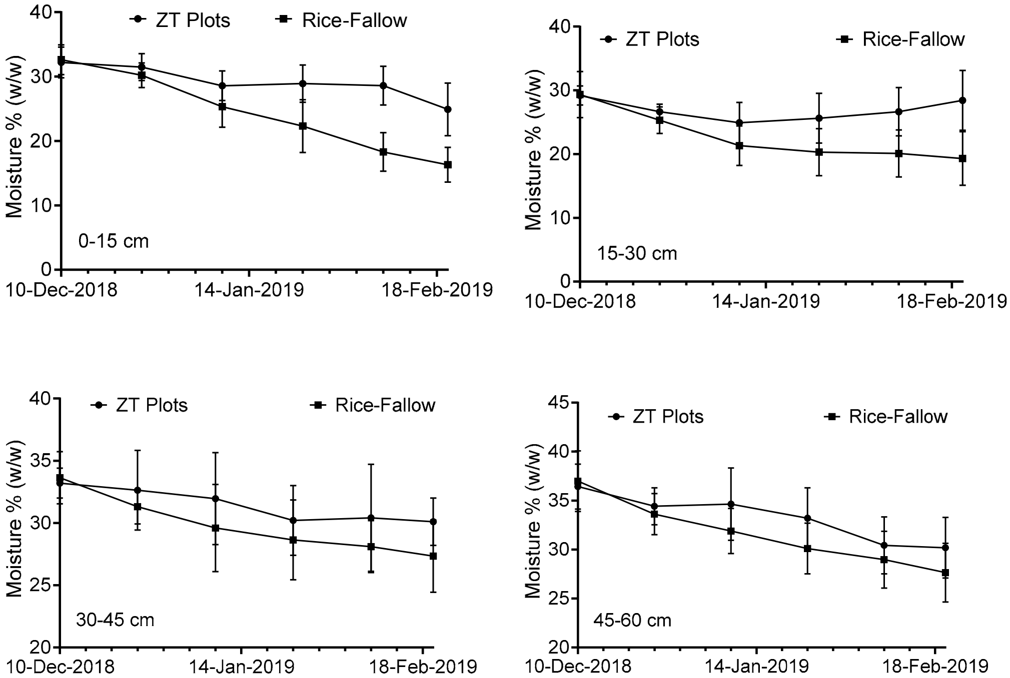

Figure 6. Comparison of soil moisture (%) between zero-tilled–mulched potato fields (ZT Plots) and adjacent rice-fallow fields (rice-fallow) (vertical bars indicate the standard deviation of the mean). source: modified from Brahmachari et al. [32].

6.5. Maintaining Soil Temperature

Application of crop residue in the field can effectively control the soil temperature by regulating the penetration of the sunlight and retaining the heat. Crop residues have an effective soil temperature moderating capacity, as thick mulching with crop residues maintains the soil temperature in a congenial range for plant growth throughout the cropping season [39,74]. In general, surface crop residues decrease the daytime soil temperature to a certain extent [67]. In dry tropical climates, this effect is very beneficial, as soil temperature rises too high for growth of the plants [75]. On the other hand, in cool climates, crop residue mulching acts as a barrier to conserve the soil temperature and maintain a congenial growing environment [76]. Moreover, crop residue incorporation and different tillage practices in crop fields act as insulating materials and generally maintain soil temperature. Crop residue management practices and conservation tillage systems affect soil temperature, and thus, soil thermal properties are also changed. It has also been reported in many articles that conservation practices mostly alter soil organic matter, bulk density, soil moisture content, and inter-aggregate contact. Therefore, these changes affect the heat capacity of the soil, thermal conductivity, and thermal diffusivity (denoted as the ratio between thermal conductivity and heat capacity) [77,78].

7. Crop Residue Management Improves the Resource Use Efficiency of Rice–Wheat Systems

Rice–wheat cropping systems are considered as the one the major sources of foods in South Asia, supplying food for 400 million people from an area of 13.5 Mha, which is mainly concentrated in Indo-Gangetic plains [79]. Irrational use of natural resources such as soil, water, and energy to keep higher productivity along with residue burning in huge quantities is the major threat in the Indo-Gangetic Plains (IGP) [80]. More than two-thirds of the rice area in the IGP is harvested using a combine harvester, generating loose rice residue during the harvesting, which restricts the subsequent field preparation and sowing. Therefore, cost-effective and hassle-free in-situ residue burning is the common practice in all of northwest India. Almost 25 Mt of rice and wheat residues are being burned in the Haryana and Punjab states only. This residue burning results in approximately 31,250,000 million MJ of energy loss along with 37 Mt of CO_2 emissions [81]. Residue burning contributes 0.05% to the total GHG emissions of India, and it is also detrimental for soil microorganisms, causing a huge loss in biomass, organic C, surface water, and soil temperature [82]. Therefore, there is an earnest need for well-managed residue management systems with good potential for resource use efficiency.

7.1. Residue Management for Soil Resources

Continuous incorporation of rice residues in soil improves the soil carbon stock and the labile pool of soil organic matter [49]. Rice–wheat systems, as exhaustive feeders, remove a greater amount of soil nutrients than those supplied through fertilizer or recycling. The residue retention facilitates nutrient conservation, as it temporarily locks the nutrient availability and helps to release the nutrients slowly throughout the crop growth period [52]. This has a remarkable contribution to nutrient conservation, and to checking the nutrient loss through either leaching or volatilization. Higher organic matter improves soil microbial colonization [55]. Better nutrient availability depends on microbial biomass and its activities in soil. Interestingly, the microbial population is positively correlated with the phyto-biomass present in soil [83]. Microbial activities strongly reflect the soil nutrient storage capacity and recycling, or, more particularly C, N, P, S, and soil organic matter. High organic matter stabilizes the soil aggregation. Rice straw in soil reduces soil erosion and subsequent major nutrient removal. Residue retention positively influences the soil physical resources, such as porosity, bulk density, and aggregate formation. Continuous application of 16 t rice residue ha^{-1} resulted in low bulk density from 1.20 to 0.98 g cm^{-3} in the 0–5 cm layer in sandy loam soil [84].

7.2. Residue Management for Water Resources

Water resource conservation is the major challenge in present-day farming. After harvesting of rainy rice, retention of rice straw in the field efficiently conserves the residual soil moisture for subsequent crops, mainly in dry tracts [85]. Mulching using rice straw not only keeps the soil moist, but also helps to moderate the soil temperature, check the weed emergence, and, most importantly, increase the yield of wheat [86]. It has been reported that 84% of the residues are wasted from rice–wheat systems [87]. Keeping rice straw in zero-till wheat in IGP increases the wheat yield, monetary return, and resource use efficiency, as reported by Erenstein and Laxmi [88] and Ladha et al. [89]. A happy seeder is used to spread loose rice residue uniformly after harvesting, and this instrument has been well adopted for conservation agriculture [90]. Retention of rice residues lowers the crop water use by 3–11% and increases the water use efficiency by 25% as compared to a no-mulching situation [91]. They also reported that rice straw improves the wheat root length by 40% as a consequence of better soil moisture storage. The 13 years of the experiment reported that continuous rice residue incorporation enhanced the wheat yield by 34.89% as compared to residue burning due to the better resource use efficiency and soil health [64].

7.3. Residue Management for Environmental Resources

The burning of rice residues is an emerging issue in rice–wheat systems, as it is considered as a cost-effective way of removing stubble. For example, in the Punjab state, 50–60% of total post-harvest rice residues are set on fire in open fields [81]. Residue burning has extremely bad effects on both the soil and aerial environment, along with human health and visibility. It is a recognized threat to rice–wheat cropping system sustainability [92]. Irrational residue waste already trims down 40% of the livestock food supply [93]. Machine-based residue incorporation with the help of microbial spray or bailing of residue for animal feeding may be a useful option for better C sequestration, soil C stock, and low global warming potential.

Alternatively, residues from a rice–wheat system may be successfully used as farm compost, livestock feed, mushroom cultivation, surface mulching agents, biochar, and biofuel, or for in-situ incorporation. Almost three tons of nutrient-rich compost can be generated from one hectare of rice straw as an farm yard manure (FYM). Phosphorous fortification with low-grade rock phosphate makes enriched compost have 1.5% N, 2.3% P_2O_5, and 2.5% K_2O [94]. Furthermore, excellent use of rice and wheat straw has been observed in the cultivation of *Agaricus bisporus* (white button mushroom) and *Volvariella volvacea* (straw mushroom). Recently, the use of crop residues as biochar is gaining importance, as it has the potential for long-term C storage, thereby resisting microbial degradation and checking GHG emissions [95]. In-situ residue incorporation has several advantages for soil physicochemical and biological properties and crop productivity, as mentioned earlier.

Therefore, the residues generated from the dominating rice–wheat cropping systems should be managed effectively and efficiently for enhancing the sequestration of carbon and maintaining the sustainability of production. Upgraded and modern technologies should be incorporated to maintain the distance from residue burning with the consideration of farmers' economic viability. Location- and soil-specific residue conservation practices would be a great researchable issue in the future.

8. Conversion Technologies for Sustainable Crop Residue Management

Growing populations will demand more food production in the future, which brings the chance of rapid crop residue generation; at the same time, the dependency of developing countries on Gulf countries for fuel is continuously increasing [96]. The intensive use of fossil fuels in the present day is causing huge GHG emissions and a range of environmental issues. The term bioenergy refers to energy derived from biomass, which is considered as a renewable resource, and is thereby gaining importance as an alternate means of sustainable energy generation [97]. The biofuels that are the main sources of bioenergy may be produced from edible food crops, such as maize, barley, sugarcane, potato, and sunflower. However, presently, biofuel production from agricultural wastes—more specifically, from crop residues—has been emphasized to facilitate residue recycling along with renewable energy generation through various conversion technologies [98]. Lignocellulosic crop residues are easily available in the food chain, and they are low-cost materials and good sources of energy [99]. As an example, in India, 500 Mt of crop residues are generated annually; interestingly, only 12.2% is used for energy production [22]. This massive amount of agricultural waste has real potential to generate various sources of bioenergy through biotransformation, which includes two general techniques: namely, thermochemical and biochemical transformation (Table 1).

Table 1. Conversion technologies for sustainable crop residue management and their possible outputs.

Techniques	Outputs
Gasification	Syngas
Liquefaction	Bio-oil
Pyrolysis	Syngas, Bio-oil, Biochar
Combustion	Electricity
Anaerobic digestion	Biogas
Alcoholic fermentation	Bio-ethanol
Photobiological hydrogen production	Bio-hydrogen
Transesterification	Biodiesel
Photosynthetic microbial fuel cell	Electricity

8.1. Thermochemical Transformation

Thermochemical conversion involves three processes: gasification, pyrolysis, and liquefaction [100]. Among these, the selection of the procedure depends on the amount and nature of residues, energy preference, financial circumstances, and environmental policy [101].

8.1.1. Gasification

This technique comprises heating of the biomass at 500–1400 °C with 33 bar atmospheric pressure in anaerobic conditions to produce a mixture of combustible gases. In this process, the carbonaceous residues transform into syngas, including hydrogen, carbon monoxide, carbon dioxide, hydrocarbon, and methane, with the existence of gasification agents [101]. This syngas is utilized as an energy carrier of biofuel, hydrogen gas, and biomethane gas. It has been reported that gasification is more efficient for producing hydrogen gas than pyrolysis or liquefaction [102]. During the gasification process, large amounts of CO_2 and CO are generated, and Watson et al. [103] reported that agricultural residues have higher CO_2 and CO contents. A fluidized bed gasifier is used for rice straw gasification [104]. Some metals, such as Ni, Ru, Cu, and Co, are also used as catalysts to boost the hydrogen and methane production.

8.1.2. Pyrolysis

This is another means of thermal decomposition of biomass that takes place at 350–550 °C in anoxic conditions. Pyrolysis transforms the organic residues into a solid, liquid, and gas mixture. In particular, liquid fuel (py-oil or bio-oil) is generated from pyrolysis, while gasification generates combustible fuel gas [105]. Based on the operating conditions, pyrolysis is divided into three different types; namely, slow, fast, and flash pyrolysis. Among them, biofuel production from fast pyrolysis is being popularized, as it is very cost effective, energy efficient, and eco-friendly, and has high (75 wt%) py-oil yielding ability [106].

8.1.3. Liquefaction

The process of liquefaction involves bio-oil production like pyrolysis, but the main difference is that liquefaction requires a low temperature and elevated pressure with the presence of hydrogen. Hydrothermal liquefaction (HTL) utilizes sub-critical water at a temperature of 250–374 °C with a 40–220 bar operating pressure to produce the bio-oil from the residue biomass [107]. The HTL method is utilized when biomass contains high moisture, as the process reduces the cost of drying or de-watering. The bio-oil production from this method ranges from 17 to 68 wt%, depending on the biomass materials used [107]. Not only the biofuel production, but also the post-hydrothermal liquefaction wastewater contains numerous numbers of nutrients that may be used further in farming practices [108].

8.2. Biochemical Transformation

This process involves some specific yeast and bacteria to transform the residue into useful energy. Three means of biochemical transformation have evolved, i.e., anaerobic digestion, alcoholic fermentation, and photobiological techniques, to produce sustainable energy [108,109].

8.2.1. Anaerobic Digestion

The method of anaerobic digestion is used in biogas synthesis from residue biomass, involving numerous numbers of microorganisms. The biogas contains mainly methane and CO_2, with 20–40% of the energy of the total biomass and a low heating value. This process can be carried out even with wet biomass with up to 90% moisture content. Anaerobic digestion has three major phases: hydrolysis, fermentation, and methanogenesis. Hydrolysis is involved in the transformation of complex biomolecules into simple biomolecules, which are transformed into alcohol, acetic acid, fatty acid, H_2, and CO_2 by the fermentation process. Methanogenesis metabolizes these gas mixtures into biogas consisting of CH_4 (60–70%) and CO_2 (30–40%) [109].

8.2.2. Alcoholic Fermentation

The residues contain fermentable sugars that can be used for bioethanol production via alcoholic fermentation with the help of yeast or bacteria. Firstly, the breakdown of complex polysaccharides into simple sugar is carried out through the hydrolysis process before feeding. After that, comprehensive steps of distillation are followed to produce the crude alcohol, containing 10–15% of ethanol [110]. The remaining residues are processed into worthy products via liquefaction, gasification, and pyrolysis.

8.2.3. Photo-Biological Techniques

Plant growth and development are extremely dependent on light. Various wavelengths cause different changes in plants [111]. Numerous wavelengths regulate different biological, physiological, and physical processes in plants. Photo-biological techniques are mainly used for H_2 gas production from microalgal biomass in anaerobic conditions [109]. This technique very often helps in regulating different biological as well as physiological processes in plants. Moreover, it helps in regulating plant growth and development.

8.3. Conversion of Crop Residues into Bioelectricity

A combustion technique is used to generate bioelectricity from lignocellulosic crop residues. In combustion, biomass is mixed with O_2 at a high temperature to produce CO_2, H_2O, and heat. The process involves the conversion of chemical energy into heat, light, and radiation energy. The biomass turns into char and volatiles, which react with O_2 and generate heat; thereafter, the heat is used to generate stream, which operates the steam turbine to produce electricity. Recently, a promising technique named microbial fuel cell (MFC) has been developed to generate bioelectricity from organic biomass with the help of electrogenic bacteria in the absence of oxygen [112]. Farine et al. [113] reported that bioelectricity generation from agricultural waste reduced a huge amount of GHG emissions, mitigating 28% and 9% of electricity emissions and national emissions in Australia [113]. It has been estimated that bioelectricity from farming residues would supply 10–20% of future electricity, as well as alleviate approximately 27 million tons of CO_2 production in the next 15 years [114]. Moreover, MFC has great potential to generate high-density power in a green and sustainable way.

9. Constraints of Crop Residue Management in Rice–Wheat Systems

The rice–wheat cropping systems (RWCS) is the major cropping system across the globe, and most of the area (around 85%) falls in the Indo-Gangetic plains [115,116]. This cropping system is spread over India, from the vast area of Punjab in the West to West Bengal in the East, but, in recent times, the sustainability of this cropping system has come into question with respect to the proper management of crop residues [117]. The traditional practices of growing rice and wheat by the farmers as per their knowledge are not only capital intensive, but also employ a large number of inputs like water, fertilizers, labor, etc. This input-intensive system furthermore emits a large amount of GHGs. Conventionally, rice fields are prepared through repeated wet tillage operations, followed by transplanting of seedlings into puddled soil. On the other hand, the wheat fields are prepared by broadcasting/drilling seeds after deep plowing of lands [118]. Seed-bed preparation in this cropping system leads to oxidizing the organic carbon within the soil, which is unfavorable for the environment. In addition, the conventional tillage process is not suitable and environmentally friendly, as it makes the soil a source rather than a sink of environmental pollutants [117]. It is estimated that around 10–14 Mg ha^{-1} crop residues were produced from RWCSs in the IGP [119]. Before initiation of mechanized harvesting, all of the residues were taken away from the field for alternative uses. A large portion of residues was leftover in the field after the introduction of mechanized harvesting using combine harvesters. This, in turn, impedes the conventional technique of seedbed preparation for the subsequent wheat crop [120]. Removal of these crop residues is labor and capital intensive. Therefore, farmers usually burn these residues to easily avoid residue removal activities. It is reported that about 75% of crop residues in the IGP are burned in RWCSs, which negatively affects the soil and the environment [21]. Though it is reported that both crop residue burning and removal are the primary cause of soil degradation in some developing countries, they have some positive impact on improving soil health status [119].

The major concern for the RWCSs is residue management. A limited amount of crop residues in RWCS are used for domestic and industrial purposes. The rest of the residues are left in the field and burned in different areas across the country [121]. The burning of rice residues is one of the major problems that adversely affects soil as well as the environment [118]. Amongst rice and wheat residues, wheat straw is used in the dairy sector, but due to the high silica content, rice straw is not used as cattle feed in different regions across the country. In addition, boosting productivity is also a major concern of RWCSs in order to respond to the pressure of population growth in India. Incorporation of rice straw causes immobilization of nitrogen due to the wider C:N ratio of rice straw, and it decreases grain yield [118]. Therefore, farmers usually burn rice residues in their fields to get rid of them, and thus assure timely sowing of wheat crops. Delayed sowing of wheat often decreases grain yield. Burning of crop residues ultimately deteriorates the soil health in many ways [122]. Thus, to avoid the burning of rice residues, numerous alternative strategies have been suggested by different experts, and one can choose the most efficient option depending on their socioeconomic and cultural status for the judicious application of rice residues [123].

10. Conclusions and Future Directions

Agriculture is the mainstay for a large number of populations worldwide. It brings bread for more than two-thirds of the population and provides food for the rest. On the other hand, the global population has been increasing at an alarming rate for the last two to three decades. This increasing rate generates pressure within the agricultural system to grow more food. Furthermore, the indiscriminate undermining of natural resources leads to the limitation of these resources. This emphasizes the need for the universal adoption and expansion of improved conservation technologies. The conservation technologies in agriculture are considered the most valuable technologies to sustain food production as well as to conserve resources. Modern intensive agricultural practices are highly input-sensitive, and uneven depletion of various natural resources results in their deficiency in many areas across the globe. Crop residue management not only improves soil physical, chemical, and biological status, but also helps in protecting the soil surface from nutrient loss.

Crop residues are often considered as waste material in terms of their economic importance, but they provide elemental carbon in soil and offer a variety of mechanisms for nutrient recycling in soil. Crop residue management helps in maintaining soil moisture content by protecting the soil surface and increasing irrigation efficiency (Figure 7). It provides food for soil microorganisms by supplementing additional soil organic matter. In addition, crop residues offer multiple ecosystem services to the environment when retained in the field after harvest. Crop residues as natural resources help to develop soil stability and maintain soil fertility. Good management practices with crop residues reduce soil erosion. Growing more food for an ever-increasing population brings the opportunity for fast residue generation. Ecosystem services from crop residues improve soil health status and supplement necessary elements for plants. Moreover, proper management practices can be useful for imparting the beneficial roles of these elements. In addition, the fuel crisis in developing countries who wish to maintain the pace of development must be addressed properly through the generation of renewable energy. Intensive use of fossil fuel produces huge GHG emissions and a series of associated environmental problems. Therefore, the alternate source of renewable energy derived from biomass in the form of crop residues will gain importance as a sustainable technique for energy generation in the near future.

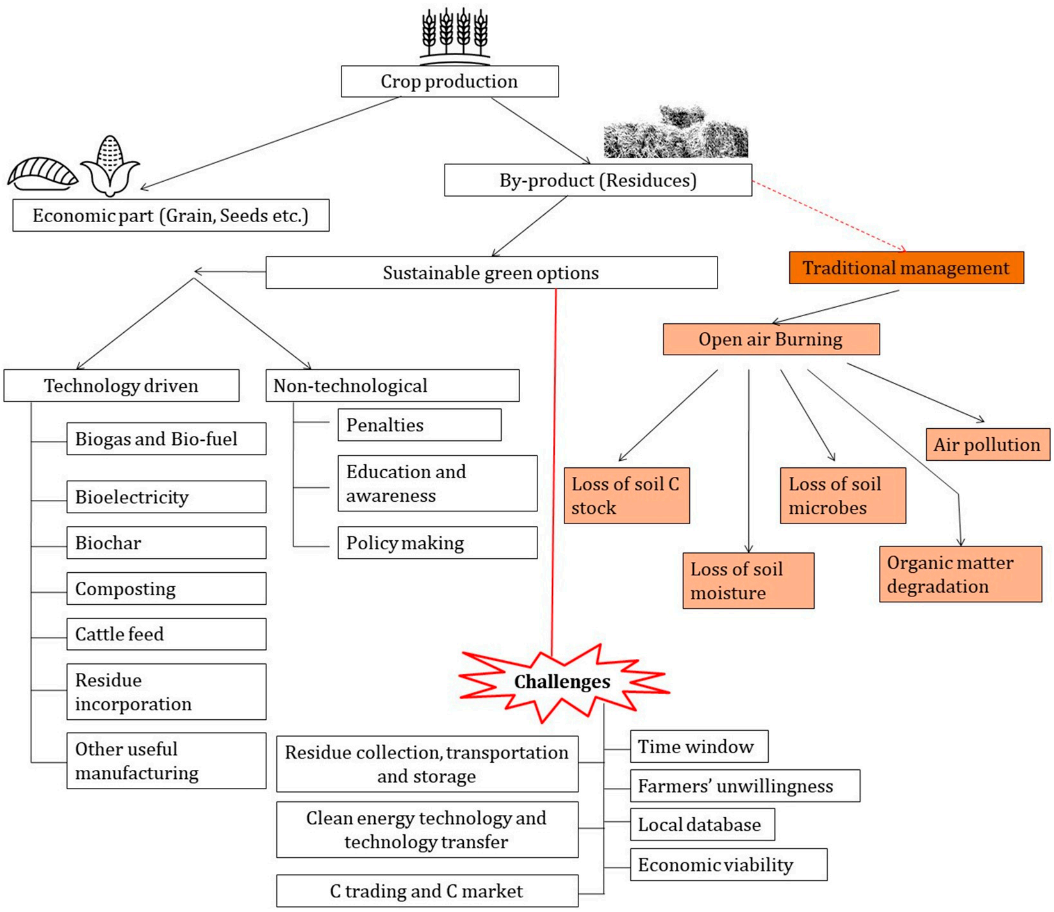

Figure 7. Schematic overview and strategies for efficient crop residue management.

Author Contributions: Conceptualization, S.S. (Sukamal Sarkar) and A.H.; resources, K.B.; data curation, S.S. (Sukamal Sarkar), S.G. and S.S. (Saikat Saha); writing—original draft preparation, S.S. (Sukamal Sarkar), S.G. and S.S. (Saikat Saha); writing—review and editing, K.R., K.B., M.S., A.H. and M.B.; visualization, K.B. and A.H.; supervision, A.H.; funding acquisition, A.H., M.S. and M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by 'Bidhan Chandra Krishi Viswavidyalaya', WB, India, Bangladesh Wheat and Maize Research Institute, Bangladesh, the 'Ministry of Education, Youth, and Sports of the Czech Republic grant number (S grant of MSMT CR)', and the 'Slovak University of Agriculture', Nitra, Tr. A. Hlinku 2,949 01 Nitra, Slovak Republic under the project 'APVV-18-0465 and EPPN2020-OPVaI-VA-ITMS313011T813'.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

C	Carbon
C:N	Carbon:Nitrogen
CA	Conservation Agriculture
CEC	Cation Exchange Capacity
CH4	Methane
DHA	Dehydrogenase activity
GHGs	Green House Gases
HTL	Hydrothermal liquefaction
MBC	Soil microbial biomass
MFC	Microbial fuel cell
N2O	Nitrous oxide

NPK	Nitrogen–phosphorus–potassium
NPMCR	National Policy for Management of Crop Residues
RWCS	Rice–wheat cropping system
SIC	Soil inorganic carbon
SOC	Soil organic carbon

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