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Review

The Fate and Challenges of the Main Nutrients in Returned Straw: A Basic Review

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Abstract: Due to containing an abundance of essential nutrients, straw has significant potential to mitigate carbon (C), nitrogen (N), phosphorus (P), and potassium (K) deficits in soil. However, a lack of comprehensive and systematic reviews on C, N, P, and K release and conversion from straw and on the impact of available nutrients in soils supplemented using straw-returning (SR) practices is noticeable in the literature. Therefore, we investigated straw decomposition, its nutrient release characteristics, and the subsequent fate of nutrients in soils. At early stages, straw decomposes rapidly and then gradually slows down at later stages. Nutrient release rates are generally in the K > P > C > N order. Nutrient fate encompasses fractions mineralized to inorganic nutrients, portions which supplement soil organic matter (SOM) pools, and other portions which are lost via leaching and gas volatilization. In future research, efforts should be made to quantitatively track straw nutrient release and fate and also examine the potential impact of coordinated supply-and-demand interactions between straw nutrients and plants. This review will provide a more systematic understanding of SR's effectiveness in agriculture.

Keywords: straw return; nutrient conversion; carbon; nitrogen; phosphorus; potassium; soils

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1. Introduction

As the concepts of environmental protection and sustainable development gain more recognition and credence, there is now a growing focus on environmental health and resource recycling, which are directly associated with human health. Scientists have made diligent efforts to seek green, low-carbon, and recycling development paths [1,2]. Currently, many studies have explored low-cost, sensitive, and highly selective methods to detect and remove hazardous substances (e.g., Cu(II), Cd(II), Ce(III)) from polluted waters [1–4], which are not only economical and efficient but also advantageous in terms of being green, reliable, and sustainable. Additionally, resource recycling is a practical management approach for achieving sustainable development. By capturing or using waste, it is possible to simultaneously meet resource supply demands and reduce waste emissions, thereby improving resource supplies and reducing emissions [5].

Straw reuse is an important and sustainable agricultural resource use method [6]. As one of the most important agricultural resources, straw is widely available in large quantities. According to recent statistics, China's straw production reached 797 million tons in 2020 and 802 million tons in 2021 (http://www.stats.gov.cn/, accessed on 1 July 2022). Straw return (SR) is currently recommended as an effective way to use straw resources [7]. Straw is rich in nutrients and exerts a notable and positive impact on soil properties and functions when reintroduced back into fields [8,9]. Therefore, to develop a scientific practice of SR, it is crucial to understand the dynamics of straw nutrient release and its fate in plant–soil systems.

SR improves soil properties and functions relevant to agronomic and environmental performance [10]. Potential SR improvements are mainly provided by enhanced nutrient supply and improved soil structure. Straw, rich in organic carbon (C), nitrogen (N), phosphorus (P), potassium (K), and other nutrients, releases these nutrients into the soil via decomposition after its return to fields, thus increasing nutrient storage capacity in the soil [11]. The extent of straw decomposition is a critical factor that greatly restricts its potential benefits. Straw decomposition is characterized by "fast and then slow" processes which are mainly controlled by straw structural characteristics, soil properties, and agronomic practices [12,13]. Straws with high C/N and abundant lignin are not easily decomposed in short-term periods. Soil nutrients have a significant impact on straw decomposition, where decomposition rates are positively correlated with soil nutrients. This may be associated with the fact that nutrient-rich soils have more microorganisms and higher microbial activities, providing favorable environments for straw decomposition [7]. Jin et al. [14] showed that straw decomposition rates were faster when the soil moisture content ranged between 15% and 22.5% and nutrient release was adequate. However, mineralization rates in soil organic matter (SOM) are much slower, which may enhance soil organic C (SOC) accumulation. Latifmanesh et al. [15] studied the effects of straw return depth on straw decomposition in a 2-year field study and reported that maize straw decomposition rates in the 0–10 cm topsoil layer were fast and favored C and N release. Contrarily, returned straw decomposition was unlikely to affect P and K release from straw, as observed by Yan et al. [16], who found that P and K content had decreased significantly by 72.22% and 88.52%, respectively, after a month of decomposition. Importantly, C and N (core straw components) have strong bonds and are gradually released due to slow straw decomposition rates. Conversely, P and K responses to straw decomposition extent are not as pronounced [16].

Straw application in fields facilitates nutrient transformation, which helps replenish soil nutrient supplies and promotes material circulation. SR is a widely accepted method used to enhance soil fertility, increase agricultural productivity, and has a substantial impact on soil C, N, P, and/or K levels [11]. Furthermore, SR improves soil texture and pH and increases bacterial flora abundance, composition, and activity, which promotes SOC accumulation [8,14]. According to previous research, C conversion rates in farmland were primarily influenced by soil pH and pore structures [17]. For example, straw application increased the pH-buffering capacity of soils, creating more favorable conditions for microbial activity and thus promoting straw C conversion to SOC [18]. Moreover, straw-treated soils showed enhanced soil aggregate stability, and the physical protection of soil aggregates weakened SOC mineralization, resulting in more straw C sequestration into SOC pools [19]. Li et al. [20] showed that microbial biomass C, labile organic C, very labile organic C, and the C management index were significantly boosted by adding straw to fields. Additionally, the nutrient pool turnover, such as that of N, P, and K, in soil was similarly regulated by straw applications. Undoubtedly, soil inorganic N is the main N form that is absorbed and used by plants, and SR has critical roles regulating soil inorganic N levels. Straw applications also improved bacterial activity, including Proteobacteria, Bacteroidetes, Nitrospirae, and Chloroflexi levels in soils and regulated N effectiveness in fields [21]. Straw N is mineralized to release inorganic N for plant uptake and utilization. Experimental evidence has now suggested that soil ammonium nitrogen (NH_4^+-N) content, directly affected by straw applications, is increased by 6.0–19.4% [22]. Li et al. [23] also identified a 2.73% increase in soil nitrate nitrogen (NO_3^--N) after straw application when compared with a no-straw scenario. Recently, several research studies highlighted SR as a potential approach for organic waste disposal to alleviate P and K deficiencies in soils [24,25]. Straw is prone to P and K release. The regulating effects of straw toward P are evident. Straw directly releases P for plant absorption and utilization [26] and also promotes stable P activation via organic matter input [27]. The improved effectiveness of soil P may be attributed to SR increasing organic C input and stimulating microbial colonization. This phenomenon expands acid and alkaline phosphatase hotspots and promotes P mineralization processes [28]. Similarly, K is a precious nutrient that affects plant development by promoting enzyme activation, photosynthesis, and photosynthetic product transport [29]. Remarkably, straw is rich in K, and nearly 90% of K^+ is rapidly released after straw is returned to fields, making K comparable to traditional chemical fertilizers in terms of fertilizing effects. Consequently, there is tremendous potential for reducing K fertilizers in straw-returned fields. Hou et al. [30] reported that continuous straw applications in northeastern rice regions maintained soil K balance and reduced K fertilizer applications by 62.2%. SR is a prospective strategy; however, research gaps exist in the systematic review of the fate and conversion of straw nutrients (i.e., C, N, P, and K) and the effects of returned straw on soil nutrient pools.

Therefore, our objectives in this review are as follows: (i) to explore straw decomposition and nutrient release characteristics; (ii) to discuss the main fate and conversion pathways of C, N, P, and K nutrients in returned straw and their effects on soil nutrient pools; and (iii) to assess SR challenges and outlooks. Our review provides crucial insights into the effects of straw on nutrient accumulation in SR models and will help junior researchers understand the basic nutrient conversion pathways and the impact of returning straw to fields.

2. Straw Types and Nutrients—An Overview

Straw refers to the stems, leaves, and (spike) components of a mature crop, typically the remaining portion of the crop after the seeds have been harvested. Straw represents a diverse range of sources and types [10,31]. The main crop straw types include cereal crop straw (e.g., rice, wheat, corn, barely, and other cereals), bean cereal crop straw (e.g., soybeans, broad beans, peas, mung beans, and other beans), potato crop straw (e.g., sweet potatoes and potatoes), and oil crop straw (e.g., peanuts, rape, and sesame) (Figure 1). In 2022, the total cereal crop area in China's major crops was 9.9269×10^7 hectares, whereas the legume, potato, and oil crop areas were 1.1878×10^7, 7.185×10^6, and 1.3140×10^7 hectares, respectively (National Bureau of Statistics 2022).

Straw is rich in nutrients; it significantly increases soil nutrients, improves soil structures, enhances crop yields, and remarkably regulates microclimates in fields [9]. Recent studies examining the effects of different straws on soils are shown in Table 1. The nutrient composition of crop straw varies depending on the straw type; therefore, the return effects may also be different [11,32]. Several studies have demonstrated that rice straw is more conducive to enhancing SOC content when compared with wheat straw, which is associated with the fact that wheat straw contains more cellulose and lignin, which are highly resistant to degradation, leading to SOC sequestration [33]. Low C/N level in rape straw is more effective in increasing SOC in dryland soils, whereas rice straw is more effective in paddy soils, as reported by Huang et al. [32]. The effects of straw nutrients depend on the straw type, climate, soil, and other conditions and must be comprehensively considered.

Table 1. A summary of recent studies using straw and their effectiveness in field applications.

Straw Type	Straw Return Approach	Soil Type	Study Method	Effects and Mechanisms	Reference
Maize straw	Rotary tillage	Silty loam	Incubation study	Corn residues with higher levels of easily decomposable substrates were mineralized by microorganisms. Both soil dissolved organic C (DOC) content and N fixation were improved.	[11]
Rice straw	Burying	Phaeozem	Field study	Straw decomposition dynamics were fast and then slow. Straw return increased soil nutrient sources and appropriately reduced K and P fertilizer applications.	[16]

Table 1. *Cont.*

Straw Type	Straw Return Approach	Soil Type	Study Method	Effects and Mechanisms	Reference
Maize straw	Nylon litterbags	Mollisol	Field study	Mixing straw with soil increased the relative abundance of stable aromatic C- and N-containing structures when compared with a straw-only treatment. In cold high-latitude regions, incorporating straw into soils enhanced maize straw decomposition and ensured more stable soil organic matter (SOM) formation.	[13]
Maize straw	Rotary and plow tillage	-	Field study	Fresh straw inputs and decomposition generated priming effects, increasing soil organic carbon (SOC) and soil total nitrogen (STN) concentrations and soil C/N.	[12]
Phragmites australis straw	Rotary tillage	Salt marshes	Indoor incubation study	Soil microorganisms elicited stress responses to short-term exogenous carbon addition, resulting in significant increases in microbial biomass (bacteria and fungi).	[7]
Corn straw	Rotary tillage	Fluvo-aquic soil	Plot study	Straw incorporation into the 0–10 cm topsoil layer decomposed faster in response to higher soil temperatures, microbial biomass C and N, and total soil porosity.	[15]
Rice and wheat straw	Rotary tillage	Loamy soil	Field positioning study	Straw addition increased the soil organic carbon (SOC) and enhanced rice yields, with rice straw showing superior enhancement effects when compared with wheat straw.	[33]
Rice straw	Rotary tillage	Soda saline-alkali soil	Plot study	Straw application significantly increased photosynthetic capacity in rice canopies and reduced mineral fertilizer use without compromising yields in soda saline–alkali rice areas.	[34]
Cotton and barley straws	Rotary tillage	Coastal saline soil	Field study	Straw return improved P availability in the soil as evidenced by higher P apparent recovery efficiency and soil P activation coefficients. Thus, straw return reduced P fertilizer levels while maintaining high seed cotton yields.	[35]
Rice straw	Mulching	Mollisol with clay soil quality	Field study	Microbial network complexity was increased when large amounts of straw were returned to fields, which contributed to C and iron cycling processes to some extent.	[36]
Rice straw; wheat straw	Ditch-buried	Sandy loamy soil	Plot study	Ditch-buried straw return significantly increased overall functional activity (fluorescein diacetate hydrolase) and growth activity (respiration rate) in 10–20 cm and 20–30 cm soils. Additionally, β-glucosidase, lipase, acid phosphatase, and arylsulphatase activities were significantly increased in different soil layers.	[37]
Wheat straw; corn straw	Rotary tillage	-	Field study	Soil organic carbon (SOC), total nitrogen (TN), available K (AK), and available P (AP) contents were higher when double-season straw return was compared with single-season straw return. Copiotrophic bacteria were better represented in soils upon corn straw return, while oligotrophic groups were better represented in wheat-straw-returned soils.	[38]

As an essential organic fertilizer resource, straw is rich in N, P, and K nutrients (Table 2). SR inevitably increases the content of the aforementioned nutrients in the soil and shows immense potential for replacing chemical fertilizers [11,39], which can significantly improve agricultural quality and efficiency and reduce environmental risks [40,41]. Drawing on official statistics and the literature, Liu and Li [42] analyzed straw resources and N, P, and K nutrient resources in China between the 1980s and the 2010s. The study reported that total straw resources increased from 4.85×10^8 tons to 9.01×10^8 tons (a growth rate of 85.77%) and total straw nutrients (N, P_2O_5, K_2O) increased from 1218.47×10^4 tons to 2485.63×10^4 tons (a growth rate of 104%) during the study period. Yin et al. [41] indicated that SR was expected to equal all K_2O, most P_2O_5, and some N levels in fertilizers, highlighting its huge advantage in reducing fertilizer applications. Generally, straw is highly abundant in nutrients, and its use can effectively improve production capacity in agriculture [35] and reduce the costs associated with agricultural production.

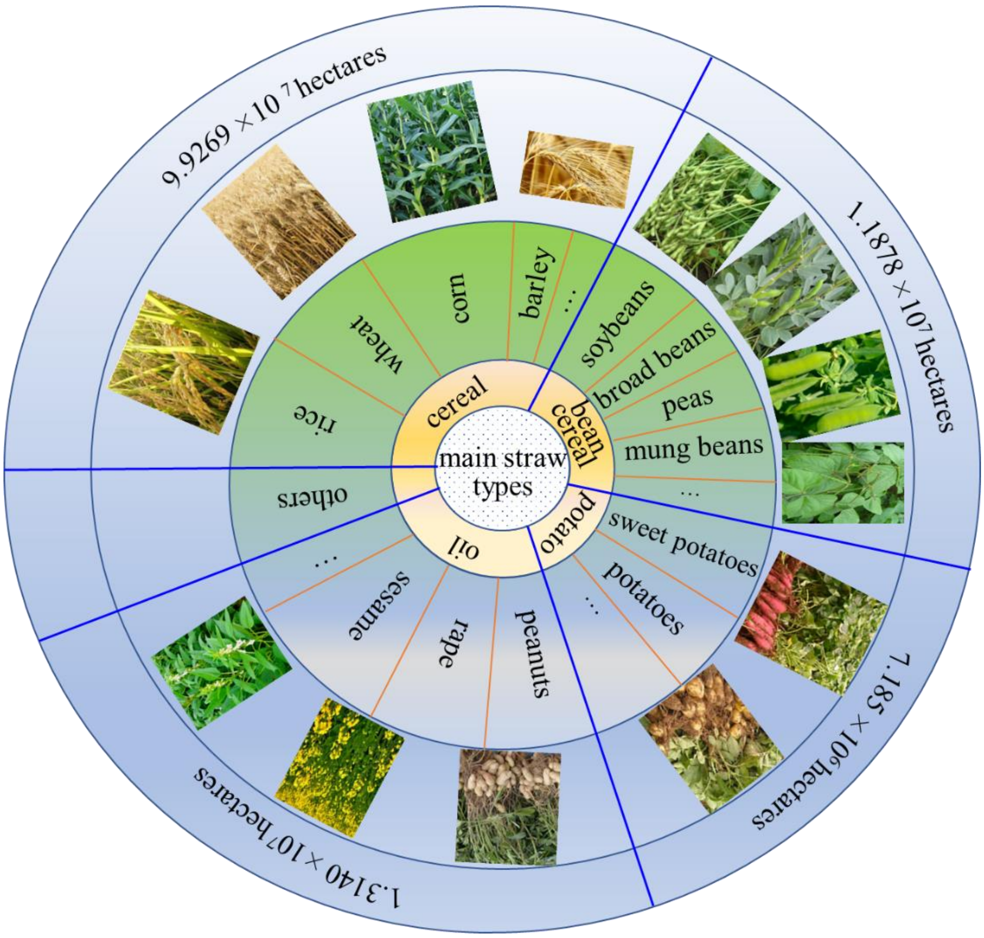

Figure 1. Schematic diagram of the main crop straw types. Note: The values in the graph are the areas under major crops in 2022 in hectares.

Table 2. Nitrogen (N), phosphorus (P), and potassium (K) nutrient content in different crops straws (on an air-dried basis).

Crops Straws	Total N, P, and K Content (g kg^{-1})	N (%)	P (%)	K (%)
Rice	28.5	28.77	4.56	66.67
Wheat	17.9	30.17	5.03	64.80
Maize	19.9	44.72	5.53	49.75
Sorghum	27.2	44.12	5.51	50.37
Millet	22.7	25.55	4.41	70.04
Barley	29.9	17.06	4.35	78.60
Other cereals	29.3	19.11	4.10	76.79
Soybeans	16.2	54.94	5.56	39.51
Mung bean	25.9	54.44	8.49	37.07
Peas	33.6	64.58	5.06	30.36
Broad bean	28.6	43.71	3.15	53.15
Beans	38	56.05	5.26	38.68
Other beans	36.3	57.02	5.51	37.47
Sweet potato	43.3	45.50	9.93	44.57
Potato	56	41.96	8.75	49.29
Peanut	33.5	48.96	4.48	46.57
Rapeseed	27.8	23.02	4.68	72.30
Sesame	20.5	52.20	23.41	24.39
Flaxseed	24	47.08	2.92	50.00
Sunflower	54	15.00	6.30	78.70
Other oil crops	31.9	27.27	5.02	67.71

Table 2. *Cont.*

Crops Straws	Total N, P, and K Content (g kg^{-1})	N (%)	P (%)	K (%)
Cotton	27	31.48	8.15	60.37
Lint	17.9	69.83	3.35	26.82
Sugarcane	21.4	46.73	6.07	47.20
Sugarbeet	21.4	46.73	6.07	47.20
Tobacco	31.1	41.80	4.82	53.38
Leafy vegetables	88.5	44.86	5.76	49.38
Rhizome vegetables	69.1	63.24	4.49	32.27
Fruits and vegetables	51.8	48.07	5.79	46.14
Average of vegetables	64.3	47.59	5.91	46.50
Banana leaves	66.6	43.39	3.45	53.15
Banana fake stems	65.5	17.86	2.29	79.85
Pineapple leaves	28.6	31.82	3.15	65.03
Pineapple stems	18.4	34.78	3.26	61.96

Note: These values represent weighted averages. The data in the table are adapted from Liu and Li [42].

3. Straw Decomposition Effects and Nutrient Release Characteristics

3.1. Decomposition of Returned Straw

Returned straw decomposition is a complex and lengthy process, involving a combination of physical, chemical, and microbial activities [43,44]. Due to its inherent biochemical stability, the steps of straw decomposition are characterized by several stages. The first stage involves rapid straw degradation, which comprises free amino acids, amino sugars, carbohydrates, and readily decomposable components. The next phase is characterized by the slow degradation of more resilient cellular structural materials, including cell walls and other difficult-to-decompose components [16].

The degree of returned straw decomposition in soil directly influences SR effectiveness, with extensive research now focusing on this topic [14]. Straw decomposition is regulated by various factors, such as straw characteristics (C/N, C/P, lignin content, etc.), soil characteristics (pH, water content, nutrient status, etc.), climatic conditions (temperature, humidity, precipitation, etc.), and also return patterns (return volume, tillage practices, straw burial depth, etc.) [14,36]. An appropriate C/N value is required to facilitate straw decomposition; the C/N value for the microbial decomposition of SOM reportedly ranges from 15 to 25. However, when the C/N value is >40 under SR, it suppresses microbial activity, which is not conducive to straw decomposition processes [45]. Once straw is directly returned to fields, it is important to supplement fast-acting N fertilizer actions in a timely manner to expedite straw decomposition and nutrient release for plant use. Otherwise, N competition between microorganisms and plants occurs, which affects plant growth and development. Furthermore, different compounds in straw decompose at varying degrees, with the following decomposition order: hemicellulose > cellulose > lignin [44]. Given that lignin is composed of an aromatic ring with side chains and covalently bonded to hydroxyl and methoxy groups, it is chemically stable and cannot be degraded easily by microorganisms, thus retaining main SOM components in soil [16]. Soil microorganisms are directly involved in organic matter decomposition and conversion, so it is vital to create excellent micro-ecological environments to promote straw decomposition. Soil microorganisms are sensitive to changes in environmental pH [46], while nutrient availability, as mediated by soil aeration, C, and N sources, shapes microbial activities [47]. Moreover, agricultural management practices (e.g., straw return methods and the number of return years) are also important in controlling straw decomposition [44]. Mulch return treatments may hinder straw decomposition processes and limit nutrient release due to insufficient contact with soil and water [8]. Conversely, mixing straw with soil not only enhances physical soil structures but also promotes the stimulation of straw decomposition and nutrient release by microbial communities. A meta-analysis by Wang et al. [9] suggested that the ideal SR duration which effectively increased SOC was 6–9 years. Similarly, Berhane et al. [48] reported that long-term SR significantly enhanced SOC storage and promoted high crop yields. These findings were supported by Yang et al. [37], who suggested that the long-term application of straw to soil improved soil microorganism diversity and activity and promoted material transformation in soil and nutrient availability to plants.

3.2. The Nutrient Release Characteristics of Returned Straw

Straw is decomposed by microorganisms and enzymes [38], which not only improve soil structure but also increase soil nutrient content. Straw is rich in elements and trace elements, and it releases many nutrient types upon decomposition. However, these nutrient release rates vary depending on their condition in straw, with the following release rate order: K > P > C > N ([13,16]; Table 3). Straw contains a significant amount of K, which mainly exists in an ionic state and easily dissolves in water during decomposition. However, P primarily exists as inorganic P (almost 60%), with the remaining portion occurring in a difficult-to-decompose organic state. C and N are the main straw components and primarily exist in highly compacted organic forms which make them resistant to physical degradation and facilitate slow nutrient release [16]. Specifically, N in straw is broadly divided into storage N (NO_3^--N, NH_4^+-N, and several small organic N molecules (amino acids, amides, etc.) that are trapped in straw) and structural N (organic N that is difficult to decompose, including N in chlorophyll, proteins (enzymes), nucleic acids, amines, amino compounds, and various vitamins). Structural N is the main N component in straw and is released more slowly when compared with stored N. Structural N must be mineralized to inorganic N by microorganisms for its gradual release [16].

Table 3. The existing forms and release characteristics of nutrients in returned straw.

Main Nutrient Elements	Forms of Existence	Release Rate
C N	Organic	K > P > C > N
P	Inorganic P (60%) and recalcitrant organic P	
K	Ionic	

N release from returned straw is significantly and positively correlated with straw decomposition, whereas P and K release rates are not influenced by whether the straw is decomposed or not. Even if most of the straw is not decomposed, P and K release rates are unaffected. Thus, SR is a valuable P and K source in the short term and a valuable N and C source in the long term [16].

4. The Fate of Straw Nutrients and Their Effects on Soil Nutrient Pools

Straw decomposition processes have an excellent potential to enrich soils and improve quality. Straw decomposition and subsequent nutrient release events occur via synergistic processes involving physical, chemical, and microbial factors, in which microorganisms are key. The nutrient conversion pathway of returned straw in soil is shown in Figure 2. Once straw is returned to fields, some nutrients are mineralized and decomposed into inorganic nutrients (1a); another portion is assimilated and used by soil microorganisms (2a); and subsequently becomes a part of SOM in the form of microbial residues (3a); and part of the hard-to-degrade components enter the SOM pool via humification (3b). Nutrients assimilated and used by microorganisms can be remineralized to inorganic-state nutrients (1b). Inorganic-state nutrients released via mineralization and remineralization can be partially sequestered in microbial reservoirs via microbial assimilation (2b), partially absorbed and used directly by plants (3), partially lost through leaching and gaseous volatilization (4), or retained in the soil [49,50].

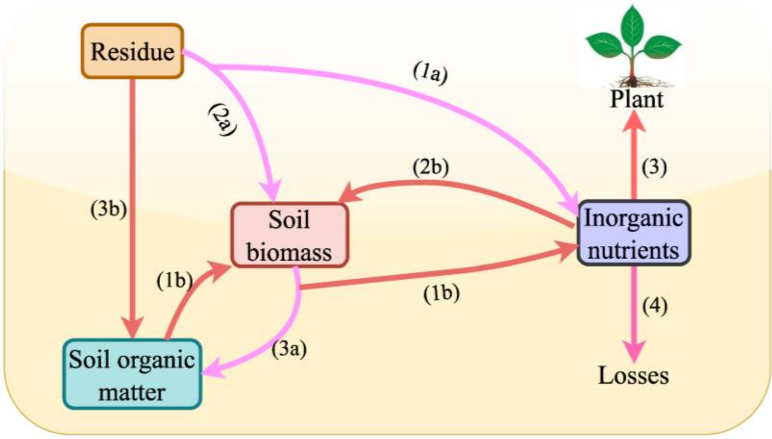

Figure 2. Nutrient conversion pathway of returned straw (adapted from Myers et al. [49]). Each conversion process is as follows: (1a) mineralization; (2a) immobilization; (3a) decomposition and degradation of microbial residues; (1b) remineralization; (2b) immobilization; (3b) humification; (3) uptake; (4) erosion gaseous loss leaching.

Straw decomposition and conversion processes are primarily conducted via two key processes, i.e., mineralization and humification. Mineralization comprises complex organic matter decomposition generated via microorganisms into simple compounds and is accompanied by mineral nutrient release. Humification, i.e., humic substance formation, comprises the formation of more complex and stable compounds from simpler ones [51]. Microorganisms have crucial roles in straw decomposition and conversion, and any factors affecting microbial activity and physiological roles influence straw decomposition and nutrient release. Straw decomposition processes occur sequentially; under favorable environmental conditions, straw decomposes more rapidly, resulting in more organic matter conversion to CO_2 and H_2O. Additionally, N and P are released as mineral salts. Conversely, when microbial activity is suppressed, this leads to delayed and incomplete straw decomposition, which reduces nutrient and energy release.

4.1. The Fate of Straw C and Its Impact on C Pools in Soil

Straw contains different C-containing compounds. SR supplements SOM and enhances soil fertility by increasing soil C inputs [52]. Straw is converted to C via microbes, where straw C undergoes mineralization and is a primary pathway for its transformation. This process generates inorganic chemicals, concomitant with CO_2 and CH_4 production. Another transformation process involves organic matter conversion to humus, which accumulates in the soil [17]. During decomposition, easily decomposed C fractions (i.e., starch, saccharose, fructose, etc.) in straw are rapidly mineralized and decomposed, while slowly decomposed C fractions (i.e., cellulose, lignin, polyphenols, etc.) remain in the soil as straw C [53].

SR significantly impacts SOC pools (shown in Figure 3), which are mainly divided into active organic C, slow-release organic C, and stable organic C pools. Indeed, active organic C mostly comprises microbial biomass C (MBC) and dissolved organic C (DOC). In contrast, slow-acting organic C predominantly consists of particulate organic C (POC) and carbohydrates. Stable organic C persists in soils and is not readily utilized [18]. Most of the C in organic material is lost as CO_2 and only a small proportion remains in the soil when straw is returned to fields. An et al. [54] conducted in situ studies to quantify the straw C contribution to microbial C by homogeneously mixing ^{13}C-labeled corn straw with soil and showed that approximately 2–5% of straw C was integrated into microbial C. Straw is integrated into soils and is accompanied by C component conversion to establish a virtuous nutrient cycle [51,55]. Active and slow-acting organic C mainly comprise transitional materials, which refer to those intermediate between fresh organic matter and humus. It has a fast rate of decomposition and actively participates in biological and chemical transformation processes in soils. Furthermore, active organic C and slow-acting organic C can be used to assess soil C pool alterations due to environmental changes [51].

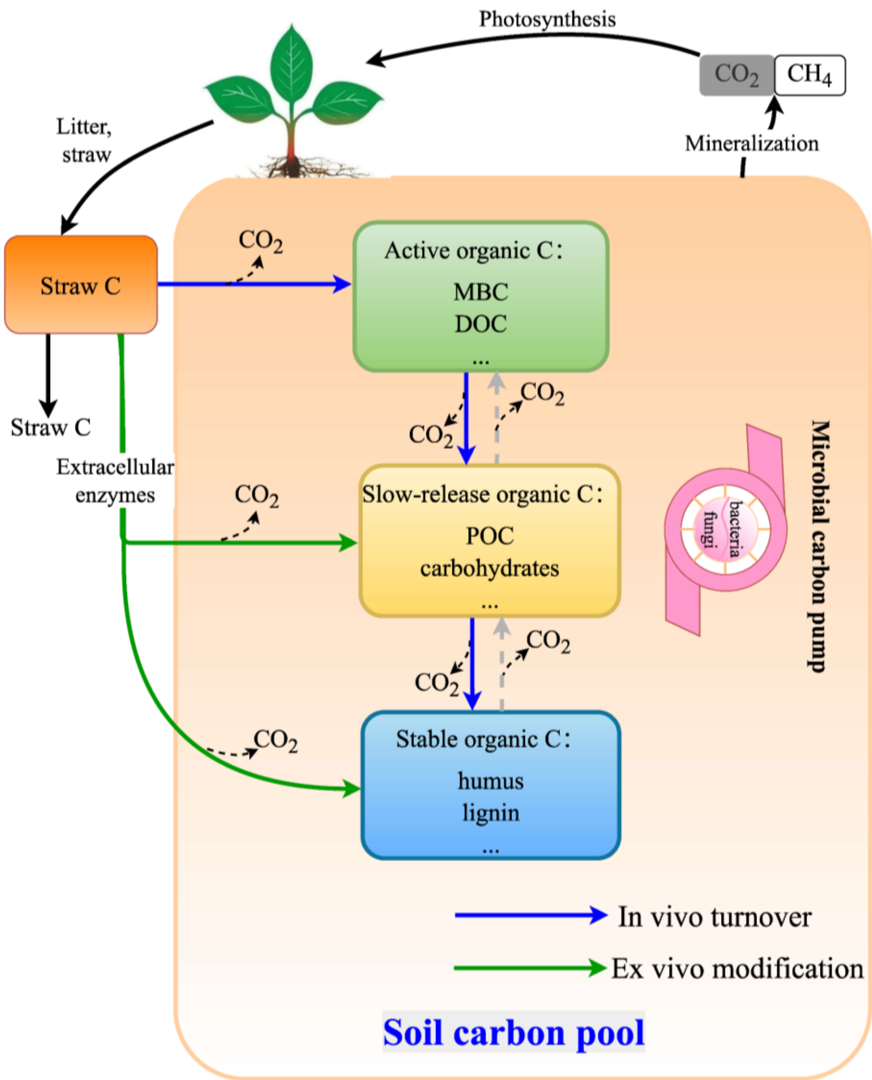

Figure 3. Main fate and conversion of straw carbon.

The principal nutrient source for soil microbes and the most active component in soil is DOC, which is mostly derived from organic straw and root biomass decomposition [56]. MBC refers to the C in living bacteria, fungi, algae, and other soil microorganisms. MBC is readily decomposed, displays high activity, and has rapid turnover rates [18]. It directly participates in ecological processes such as nutrient cycling, litter decomposition, and organic matter conversion, thus reflecting the high conversion efficiency of SOM to microbial biomass. In other words, MBC has decisive roles in assessing soil organic C storage. POC acts as a temporary organic C, and its decomposition is necessary for generating DOC and MBC, while its sequestration is a prerequisite for forming stable organic matter (humus).

Notably, active organic C and stable organic C exist in a dynamic equilibrium, and their transformation involves different biological, chemical, and physical processes. Microorganisms (e.g., activity and community structures) are essential factors influencing straw decomposition and have a key role in organic C formation, conversion, and decomposition, which mainly encompasses both in vivo turnover and ex vivo modifications [57], as shown in Figure 3. Microorganisms first degrade macromolecular plant C by secreting extracellular enzymes, then synthesize their own biomass via assimilation, and finally transport microbial C to the soil via growth and death processes. Considering C transformation in the soil, some activated organic C is decomposed to CO_2 and released into the atmosphere via microbial processes. The remaining organic C is converted to organic matter in microbial communities to form stable C. Additionally, activated organic C also adsorbs minerals from the soil to form stable organic mineral complexes in the soil. Furthermore, straw application improves the physical structure of soils, enhances soil aggregate formation [19], and promotes activated organic C conversion to stable organic C. This conversion is a relatively slow process which takes a long time to accumulate and maintain. Conversely, several processes, such as urease, redox reactions, and acid–base reactions help decompose stable C to active organic C [55].

SR, as an effective straw reuse mechanism, exerts two-sided effects on SOC. SR is a promising strategy to boost SOC. A possible explanation for improved SOC is that nutrients released by straw increase soil aggregate formation, which in turn protects SOC and thus enhance its storage [32,58]. Furthermore, organic matter released during straw decomposition significantly increases soil microorganism activity and accelerates their metabolism, which helps convert exogenous C to active C and positively affects SOC [59]. It is important to acknowledge that SR significantly improves SOC but is also prone to triggering effects that speed up SOC decomposition and increase soil C emissions. Non-stable organic C pools in soils are more sensitive to changes in external conditions (e.g., tillage disturbances and vegetation type shifts) and more susceptible to mineralization losses, which are clearly detrimental to C sequestration. Hence, SR effects on SOC depend on a balance between SOC accumulation and decomposition in response to exogenous organic C inputs, which may be due to different factors, such as soil texture, water content, and temperature.

Returning straw to soils significantly improves active organic C pools [60]. The "equilibrium" state of soil C pools is determined by C inputs from crop residues and C losses from organic matter decomposition to CO_2 and/or CH_4 under anaerobic conditions.

4.2. N Transformation Pathways in Straw and the Effects on Soil N Pools

Returned straw is an essential N source in agricultural production, and straw N has three main destinations under soil microorganisms, i.e., uptake and utilization by plants, retention in soil, and loss in various forms [61]. Straw N predominantly exists as organic N, with small amounts of free N-containing ionic compounds (mainly NH_4^+-N and NO_3^--N). N conversion of straw during decomposition processes is shown in Figure 4. Straw N is absorbed and fixed to soil microbial biomass N (MBN) by microorganisms. Additionally, a portion of N is mineralized to NH_4^+-N and NO_3^--N for plant use, while other portions form humus. However, a fraction is also susceptible to loss via gas and leaching. Critically, the utilization of straw during the growing season is limited and a significant N proportion remains in the soil as organic matter N even after straw mineralization. Therefore, a N portion in soil may be detected as straw N.

N mineralization–fixation processes by soil microorganisms exert a significant impact on N supply and loss in soils [62]. SR provides a rich C source for microorganisms, increasing microbial activity and enhancing N uptake and sequestration. Microorganisms undergo rapid metabolism while immobilized microbial N returns to the soil for plant use after microbial death. Consequently, MBN is considered an unstable N component in soils [62]. Generally, straw with a low C/N ratio is more easily mineralized and decomposed by microorganisms after being returned to fields. Straw N conversion is mainly influenced by the microbiota. Ammonifiers play key roles in mineralizing organic N, while nitrifiers (i.e., nitrite and nitrate bacteria) oxidize NH_4^+-N under aerobic conditions. Denitrifiers, on the other hand, reduce NO_3^--N under anaerobic conditions. It should be noted that NH_3, NO_2, N_2O, and other compounds are present during denitrification processes. Plants have a greater ability to absorb and convert inorganic N (i.e., NH_4^+-N and NO_3^--N) to plant N via biological N fixation. In contrast, straw with high C/N ratios is likely to stimulate the microbial fixation of inorganic N in soils after straw is returned to fields (Figure 4; [63]). Moreover, inorganic N has a higher risk of loss, which partially occurs via leaching processes.

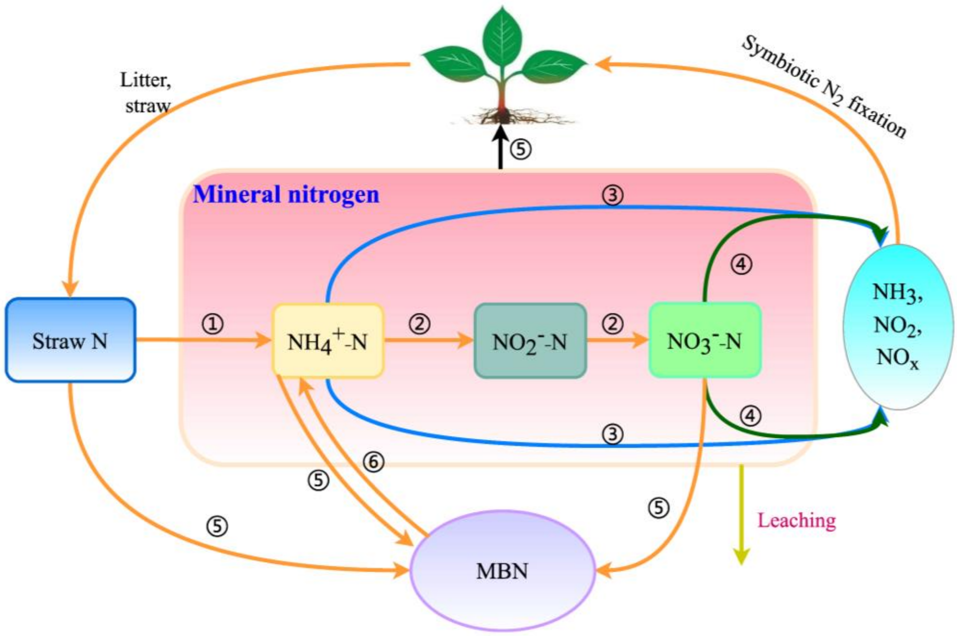

Figure 4. Main fate and conversion of straw nitrogen. Notes: ①, mineralization (ammonification); ②, nitrification; ③, ammonia volatilization; ④, denitrification; ⑤, immobilization; ⑥, remineralization.

When straw is incorporated into the soil, it contributes N to the soil and facilitates the interconversion of various nitrogenous compounds. Briefly, MBN is the most active component in soil; it has a high turnover rate and plays vital roles in soil N cycles [64]. Soil microorganisms regulate various biochemical reactions and are key players in organic matter accumulation and/or mineralization. MBN is an essential indicator of soil microbial abundance and activity. Inorganic N (NH_4^+-N and NO_3^--N) is the main N form taken up by plants from soils, and its content reflects the soil's ability to supply N as well as being the driving raw material for nitrification and denitrification reactions. Nitrogen oxides (NO_x), often recognized as air pollutants, are also inevitably produced after straw is returned to fields.

SR effectively improves N mineralization and utilization [65], which is mainly attributed to the positive impact of soil microbial activity, community structures, and functional diversity upon straw application. Through SR, straw C provides energy and nutrients to soil microbes, thereby boosting growth. Zhang et al. [66] reported a significant increase in the relative abundance of Proteobacteria and Nitrospirae after SR, thereby affecting N transformation and metabolism. Straw substantially improves the activity of N-transforming functional bacteria. Ammonia oxidation microorganism populations increase significantly, and ammonia-oxidizing bacteria (AOA and AOB) facilitate nitrification processes [67]. Both *nir*K and *nir*S-type denitrifying bacteria, which drive nitrate dissimilation, also exert positive responses to SR [68]. Not only does SR regulate N transformation, but it also positively affects soil N retention [38]. Using a ^{15}N labeling method, Liu et al. [69] observed that straw application significantly enhanced the active organic N fraction (i.e., particulate organic matter N, dissolved organic N, and microbial biomass N) and mineral N levels (i.e., NH_4^+-N and NO_3^--N) in soils, thereby improving N supply capacity. Moreover, SOC enhanced by SR also had an increased cation exchange capacity, which prevented NH_4^+-N leaching and improved NO_3^--N retention owing to deprotonated carboxyl groups [63].

4.3. Straw P Conversion and Its Effects on Soil P Pools

The main P destinations from returned straw are similar to C and N destinations, with some P absorbed directly and used by plants, other P fixed by microorganisms, and a portion converted to soil organic P, while P erosion, runoff, and leaching losses also occur [70].

P is an essential element for plants, and SR is an important P source. Similarly, P is an important component of many compounds in plants and participates in many plant metabolic processes [71]. P required for plant growth and development may be generated via soil microbial turnover, while microbial biomass P (MBP) is the most active part of the soil P pool. Organic P is an important P source for plants, but it cannot be directly absorbed and must be converted to inorganic P via mineralization [72]. Furthermore, available P is a fraction of the P available to plants for absorption, mainly including all water-soluble P, part of mineral surfaces P, organic P, and some secondary P compounds (Figure 5). Organic P, MBP, soluble P, and inorganic P in soil are always in a dynamic cycle to maintain a virtuous P cycle.

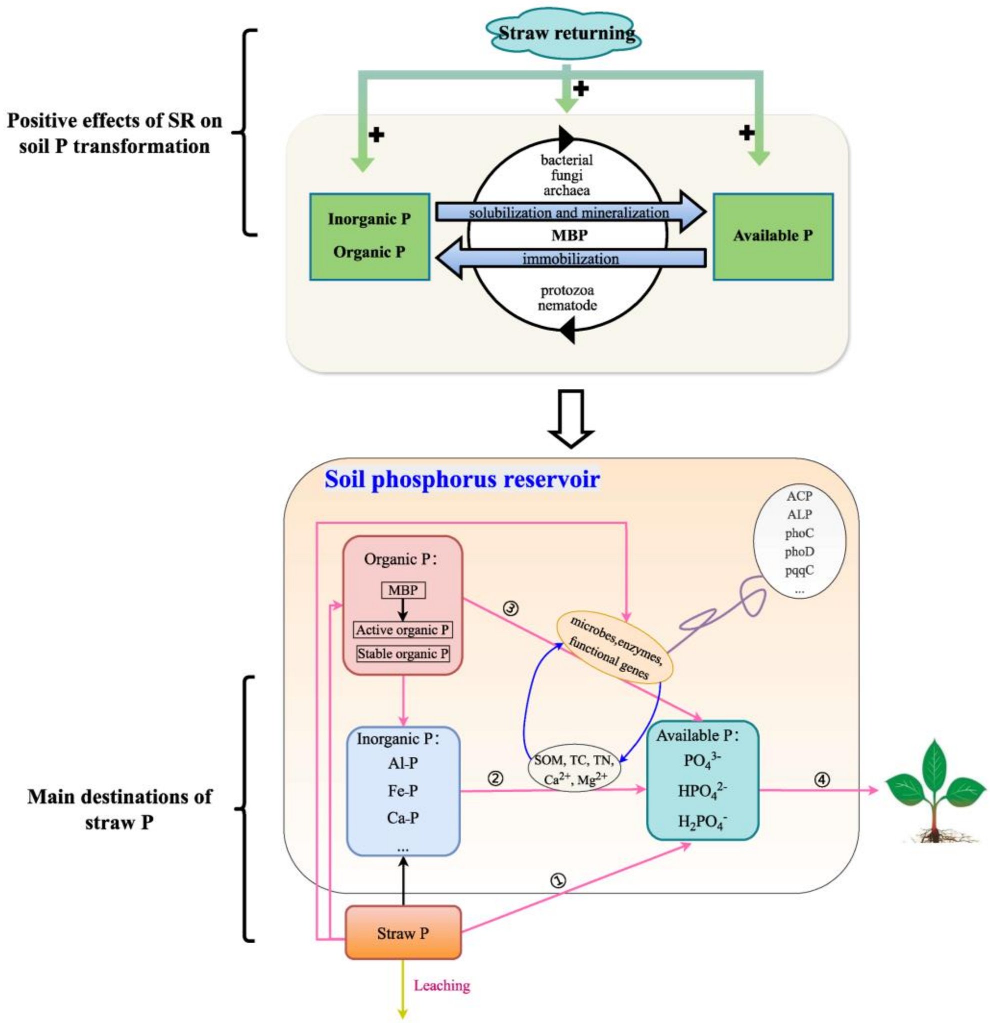

Figure 5. Main fate and conversion of straw phosphorus. "+" represents a positive effect. Notes: ①, input; ②, dissolution; ③, mineralization; ④, uptake.

SR, as an essential source of soil P input, has a significant impact on soil P content. Organic P mineralization and inorganic P dissolution are two critical conversion pathways for soil available P [73], as shown in Figure 5. Increased available P content in soil may be attributed to P release by straw and competition for P sorption sites caused by organic acids generated during straw decomposition. More specifically, organic acids produced by straw form chelates with insoluble substances (e.g., Ca-P, Mg-P, and Al-P) to facilitate P release [38]. Increased SOM content due to SR also reduces P sorption in soil, while adding straw C enhances microbial activity and promotes soil P activation [74]. Fei et al. [75] showed that inorganic P, available P, and soil microbial biomass P were significantly enhanced after SR, which in turn promoted soil P effectiveness. Acid phosphatase (ACP) and alkaline phosphatase (ALP) activities are essential constraints on soil organophosphorus mineralization processes. SR significantly improved functional gene abundance for P conversion (e.g., *pho*C and *pho*D) and increased ACP and ALP activity and functional diversity [76], which facilitated organic P mineralization to available P. Evidence has also suggested that increased phosphatase activity had a positive impact on soil P availability for plants, as phosphatases stimulated the hydrolysis of oxides and mineral bound P, ester phosphate bonds [77]. Han et al. [26] similarly indicated that soil phosphatases increased significantly after SR, which enhanced the hydrolysis of esters and anhydride of phosphoric acid, thus releasing phosphate for direct use by plants.

Thus, SR serves as a compensating measure to enhance P content in soil. In addition to P content in straw, SR also regulates P mobilization processes by influencing different microorganisms. The content and proportion of inorganic and organic P determine the effective and potential P supply capacity in soils, respectively. Straw can be returned to fields as a P fertilizer to increase available P. However, due to the relatively low P content in straw, competition for P between microorganisms and plants may occur after SR; thus, the application of some P fertilizer with the returned straw is required [35].

4.4. The Fate of K in Straw and Soil K Pool Responses to Straw Application

Straw contains high K levels; approximately 80% of the K absorbed by crops is retained in straw. K mainly exists as K^+, which is soluble in water and released [26,78]. Returned straw is an excellent fast-acting K fertilizer resource and quickly releases K to replenish soil K pools. SR directly enhances water-soluble K content, which is directly available to plants but partially susceptible to leaching losses (Figure 6).

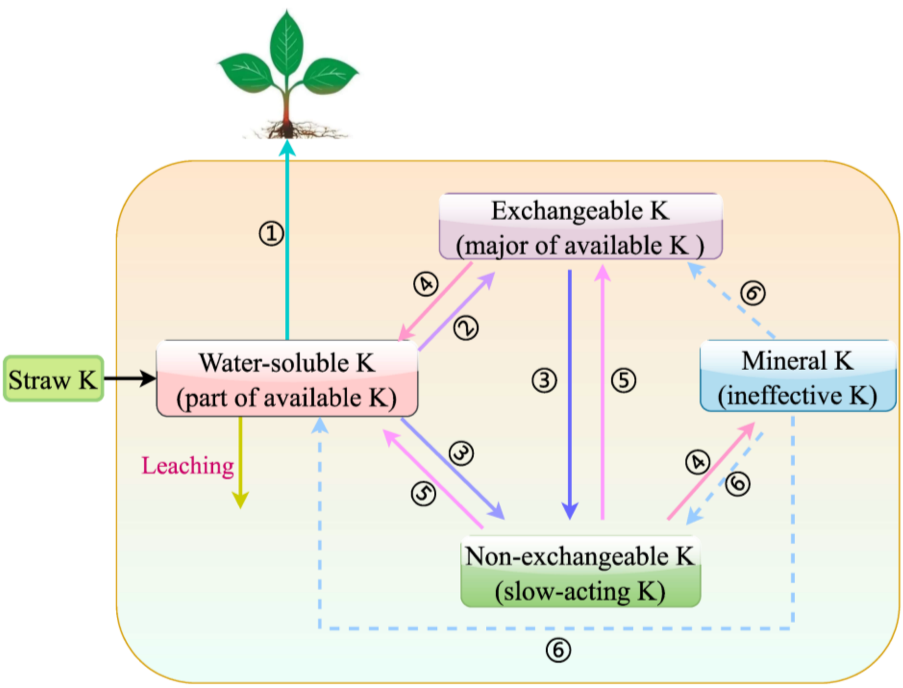

Figure 6. Main fate and conversion of straw potassium. Notes: ①, uptake; ②, adsorption; ③, fixed; ④, desorption; ⑤, release; ⑥, weathering. The dashed line indicates that the weathering process of the mineral K is slow.

Soil K is classified into three types based on its effectiveness for plants: available K (i.e., water-soluble and exchangeable K), slow-acting K (i.e., non-exchangeable K), and ineffective K (i.e., mineral K) [79]. Available K is often used as a primary indicator to evaluate K effectiveness in soils. Water-soluble K remains in aqueous soil solutions and is directly absorbed and used by plants. However, this K fraction occurs at low levels and is only a minor part of the available K. Exchangeable K is the primary component of available K and generally refers to the K adsorbed on the surface of the soil colloid. Non-exchangeable K is an available K reservoir and is released to replenish the available K content in soils when levels are low; however, inefficient K in soil is less likely to be used by plants. K is easily dissolved when straw is returned to fields, which increases soil available K levels for plant absorption and use [58]. Additionally, a rapid increase in soil available K leads to the conversion of some available K to slow-acting K, which is advantageous for improving soil fertility. SR not only returns nutrient K but also promotes mineral K release. According to Wang et al. [80], K in a readily available form in straw is rapidly released into the soil after straw is returned to fields. Their results also showed that a 25.6% increase in K was available to plants use after straw was returned. A study by Zhu et al. [58] indicated that SR enhanced exchangeable and non-exchangeable K content in soil and significantly improved the K supply capacity. Indeed, returned straw released organic acids, which easily formed metal–organic complexes with metal ions in mineral structures, thereby activating mineral K and prompting its release [80].

The various soil K forms are in a dynamic equilibrium and regulate each other. An increase in soil soluble K concentrations triggers the conversion of some K to slow-acting or mineral K; while, conversely, this process also proceeds in the opposite direction [81]. Notably, K is quickly released from straw, and often a lack of synchronization exists between K release and uptake by plants. Therefore, returning straw to fields usually requires the application of K fertilizers [80].

5. SR and Associated Challenges

Undoubtedly, SR improves soil physicochemical properties, nutrient availability, and the soil biota. Although we mainly focused on the effects of straw on soil macronutrients (N, P, and K) (Figures 3–6), the replenishment of other soil micronutrients such as sulfur, iron, manganese, zinc, and copper by straw [82] cannot be ignored. Wang et al. [83] reported that SR was an effective response to soil degradation due to SOC and nutrient loss in the black soil areas of Northeast China. According to Saha et al. [84], straw application was a viable and durable option for soil micronutrient reserves, correcting micronutrient deficiencies in a rice–wheat cropping system. In terms of nutrient improvement, returning straw to fields has huge potential. Nevertheless, when straw is decomposed, it tends to lose some nutrients by leaching or gaseous volatilization (Figure 2). Thus, while straw provides many soil nutrients, it also brings some negative impacts, including non-point resource pollution and greenhouse gas emissions [61,85]. Liu et al. [86] reported that N and P concentrations on the surface water in paddy fields increased significantly after straw was returned, and consequently, surface pollution increased. Moreover, chemical oxygen demand levels in straw-treated field water were elevated by organic material decomposition (hemicellulose and cellulose), which deteriorated water quality [87]. Several studies also reported potential water pollution and eutrophication due to higher N availability after residue incorporation [88,89]. It should be noted that SR potentially accelerated the emission of soil GHG and increased GWP [90]. This was primarily due to the fact that SR improved soil microbial activity and significantly accelerated decomposition of inherent organic C into CO_2 and CH_4 (Figure 3; [91]). Xia et al. [63] reported that SR effectively stimulated nitrification/denitrification and soil urease activities, resulting in a noticeable increase in N_2O (21.5%) and NH_3 emissions (17.0%) in upland fields.

In addition to pollution problems caused by nutrient loss, straw application also enhanced metal bioavailability [92]. Significant increments in methylmercury bioaccumulation in wheat and rice grains were reported following straw application [93]. Possible mechanisms for increased metals included dissolution, complexation, methylation, and/or physiological effects [92]. Straw decomposition also decreased the soil pH, which promoted metal dissolution [94]. Also, complexation of metal and dissolved organic matter, to some extent, promoted metal uptake by microbial and biological processes [95]. Thus, improved crop physiological traits mediated by straw application may contribute to metal bioavailability [93].

Straw application also influences soil microbial community composition. Yan et al. [56] indicated that SR enhanced microbial community abundance. When compared with a no-straw-return treatment, straw return increased Gm^+-bacterial and Gm^--bacterial levels [18]. Several studies also reported that SR enhanced nitrite reductase (*nir*S and *nir*K) copy numbers [96,97]. Indeed, soil nutrient cycling processes are very complex, and the associated microbes are diversified and complicated. It is an important breakthrough to understand the effect of SR at the molecular level.

Bearing in mind this evidence, SR poses several practical and environmental challenges (e.g., organic, greenhouse gas, and heavy metal pollution issues), which deserve our attention. Undoubtedly, future research should also focus on the following:

(i) One of the main limitations to overcome is quantitative studies on nutrient release from straw decomposition.

Using SR, nutrients (C, N, P, and K) are returned to fields, but quantitative studies examining the transformation processes of different nutrients must be increased. In this review, we mainly focused on the qualitative description of the main destinations of straw nutrients, while quantifying their contribution has been lacking in the literature. Also, new material cycling techniques, such as molecular biology [98], gene microarray [99], and isotope tracing [100], are emerging and can provide insights on the distribution, existence patterns, and dynamic balance of different nutrients in returned straw ecosystems. Thus, examining the nutrient cycling pathways and stability mechanisms may become more feasible using these technologies.

(ii) Focus on the optimization of straw mineralization measures and the synchronization between straw nutrient release and crop absorption.

In general, the in-season use of returned straw is limited; thus, it is vital to enhance straw mineralization procedures to maximize its seasonal fertilization potential. Straw structures are relatively stable and have a slow natural decomposition. Evidence has suggested that slow straw decomposition may reduce seedling quality [101]. Thus, the application of decomposition agents after SR is required to improve straw utilization rates at this stage [102]. Notably, although decomposition agents promote straw decomposition, this rapid decomposition accelerates N fixation by soil microorganisms and reduces soil N effectiveness. On the other hand, organic acids, CO_2, and phenolics are increased by this acceleration [103]. Thus, such actions are unfavorable for crop seeding. Future research must optimize ripening agent formulas, application times, and quantities across different scenarios to enhance their promotional effects on straw decay. Typically, later crop stages are manifested by vigorous growth, with high demands for nutrients. Indeed, further research on nutrient adsorption-sustained release from straw is required to meet the growth requirements of crops.

(iii) Water eutrophication effects due to coordinated C/N after straw return are concerning.

There are many ways to reuse straw, e.g., returning directly to fields, pyrolyzing, and cycling back to fields (i.e., generating C-rich material-biochar). However, regardless of how straw is incorporated into soil, C/N coordination effects between soil and plant growth requirements are poorly defined in the literature. According to the current consensus, high C/N straw intensifies the conflict for N between crops and soil microorganisms, thereby limiting crop growth and reducing yields [104]. SR combined with reasonable N fertilizer transport is a meaningful way to alleviate the contradictions between straw decomposition and crop growth. It is worth noting that nutrient demand is low during crop seedling stages, and the co-application of straw and N fertilizer is likely to generate a N surplus, which may also increase the possibility of non-point source pollution. Therefore, in the future, consideration should be given to reducing N fertilizer applications at initial crop stages.

The overall effect of SR must be holistically considered to balance agricultural and environmental benefits. Considering SR's benefits, we must focus on reducing or even cutting off straw nutrient loss pathways and rationally applying straw in practice. We must also improve the balance between nutrient supply in soils and the combined nutrient demands of straw decomposition and crop growth, which ultimately favor high crop productivity.

6. Conclusions

Straw is rich in nutrients, and its return to fields enhances soil nutrients, improves soil fertility, and increases crop yields. Straw structure and components form the intrinsic properties and determinants required for straw decomposition, while soil microorganism type, number, and activity are its external drivers. The final destinations of straw nutrients (e.g., C, N, P, and K) are threefold: they partly replenish soil nutrient pools, partly enhance inorganic nutrient content, and partly are lost. Generally, SR provides a favorable soil environment for plants and has significant agricultural benefits. However, adverse environmental impacts such as water and air pollution cannot be ignored.

This review contributes to the literature by highlighting the role of SR in soil nutrient reservoirs and elucidating the fate of its different nutrients. In the future, scientists must quantitively analyze nutrient transport processes in straw, clarify nutrient supply–demand contradictions between straw and crops, and comprehensively examine C/N coordination.

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