Does Straw Returning Amended with Straw Decomposing Microorganism Inoculants Increase the Soil Major Nutrients in China’s Farmlands?

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Abstract: Although straw-decomposing microbial inoculants (SDMI) are capable to generally promote the fertility of straw-amended soils, their impact on the release of individual soil major nutrients remains controversial. Additionally, the combined effects of SDMI and environment/management on various forms of nutrients remain poorly documented. To fill these research gaps, we conducted a meta-analysis study using 1214 paired observations from 132 field trials in China. Our results showed that SDMI significantly increases the total and available concentrations of nitrogen, phosphorus, and potassium in soil ($p < 0.05$), although increases in nutrients varied with different conditions. Moreover, mean annual precipitation (MAP) had significant correlations with the effects of SDMI-amended straw on soil total nitrogen ($p = 0.008$) and available nitrogen ($p = 0.0006$). The effect of SDMI-amended straw on soil total phosphorus and soil available potassium was mainly correlated with soil organic matter ($p = 0.032$) and MAP ($p = 0.049$), respectively. Our findings indicate that SDMI-amended straw can have a measurable impact on the status of soil major nutrients. In particular, the application of SDMI-amended rice straw with an initial C/N ratio of $\leq 15$ to neutral soils in temperate and subtropical monsoon climates is a promising strategy.

Keywords: soil fertility; straw-amended soil; microbial inoculant; agricultural management practices; meta-analysis

1. Introduction

The agricultural sector in China produces over one billion tons of crop straw annually, accounting for about one-third of global straw production [1]. Crop straw contains nitrogen (N), phosphorous (P), potassium (K), and other trace elements that, in turn, contribute to soil fertility and crop growth [1,2]. However, the release of these elements to the soil depends on the decomposition rate of straw components, such as lignin, cellulose, and hemicellulose [3,4]. The effect of straw-decomposing microbial inoculant (e.g., cellulose-decomposing bacteria, defined as SDMI in this paper) on the decomposition rate of crop straw has been investigated in several studies [5–8].
Through a meta-analysis, our previous study found a significant positive correlation (p < 0.0001) between the effect of SDMI on straw decomposition rate and crop yield [7]. However, it is still not clear whether straw decomposition increases yield by promoting soil fertility. Differences in the abundance of soil N, P, and K (hereafter, N, P, K), with or without the application of SDMI, can help to elucidate the efficacy of SDMI on soil fertility as well as the mechanism of straw decomposition rate and crop yield. In a recent study, SDMI application accelerated straw decomposition and increased soil nutrients through the stimulation of soil microbial activity, thus increasing crop yield [9]. However, there are still uncertainties in regard to the effects of SDMI on the contents of different forms of soil nutrients. This is of particular importance, as the efficacy of SDMI is strongly influenced by the environmental factors and agricultural management practices [10–12]. For instance, the incorporation of SDMI-amended straw to acid soil under rape cultivation increased soil total and available N levels by 3% and 4%, respectively, while it decreased soil total and available P levels by 3% and 22%, respectively [13]. In contrast, in a long-term rice–wheat rotation, SDMI application decreased and increased soil total and available N by 2% and 5%, respectively [14]. In Shajiang black soils, SDMI application increased and decreased the concentrations of soil available and total K by 7% and 2%, respectively [15]. These inconsistent results call for a comprehensive review of the existing data to better understand the dynamics of various forms of soil major nutrients under SDMI application.

A recent meta-analysis study showed that the effects of SDMI application on straw decomposition and crop yield vary significantly under different affecting factors (i.e., climates, land use type, soil condition) [7]. For instance, compared with neutral soils (pH 6.5–7.5), SDMI significantly increased the rate of straw decomposition and crop yield in acid soils (pH ≤ 6.5) and alkaline soils (pH > 7.5). This might be attributed to the stronger competition between native microbial population and SDMI in neutral soils, restricting the SDMI efficacy [16]. Similarly, variations in soil properties and climate could also cause fluctuations in the abundance, composition, and activity of the soil native microbial community and thus influencing the SDMI impacts on nutrient cycles [17–19].

To date, there has been no overall assessment of the combined effects of SDMI-amended straw and the affecting factors (environmental factors and agricultural management practices) on soil N, P, K, which might be achieved by regression analyses [20–22]. Simple linear regression model revealed that straw returning caused significant increase and decrease in soil organic carbon (SOC) content and soil N losses, respectively [20]. In addition, soil C sequestration was correlated to the straw C input [21].

Here, we report, for the first time to our knowledge, a comprehensive meta-analysis study to explore the effects of SDMI-amended straw on soil N, P, K. This study was conducted in croplands of China via collection of 1214 data from 132 field experiments. Altogether, we aimed at: (1) evaluating the impacts of SDMI application on various forms of soil N, P, K; (2) exploring the overall effects of environmental factors and agricultural management practices on various forms of soil N, P, K; and (3) identifying the key environmental factors regulating the effects of SDMI-amended straw on various forms of soil N, P, K. The results of this study are hoped to provide guidance for the evaluation of the effects of SDMI on soil fertility and nutrient status, thus helping the stakeholders and farmers improve the management of straw resources.

### 2. Materials and Methods

#### 2.1. Data Collection

In this work, we used Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (http://www.prisma-statement.org/, accessed on 1 September 2022) for data collection, analyses, and presentation (Table S1). We searched for relevant empirical studies, investigating the effects of SDMI on soil N, P, K using ISI Web of Science and China National Knowledge Infrastructure (CNKI) database. The search was performed between January 2001 and December 2019 using the following search terms: (straw returning OR crop residue incorporation OR crop straw OR crop residue OR straw degradation)
AND (decomposing agent OR decomposing microorganism OR decomposing microorganism OR straw decomposition OR microbial inoculants OR straw decomposition OR microbial inoculants). In order to select the appropriate studies: (1) the experiments should have been conducted in Chinese croplands; (2) the experiments should have involved the application of SDMI-amended straw to the soil but not in situ SDMI application to straw; (3) the studies should have reported the relevant data of total and available N, P, K in both SDMI and non-SDMI (i.e., control) amended soils; and (4) both SDMI and non-SDMI treatments should have been under identical management (e.g., irrigation frequency, fertilization scheme, rate of straw returning, and experimental duration) (Figure S1). Considering these constraints, the complete dataset was composed of 1214 observations from 132 studies, including 257, 127, 105, 314, 93, and 318 observations from total N, available N, total P, available P, total K, and available K, respectively. Of all field experiments, 99 measured soil total N, 47 measured soil available N, 35 measured soil total P, 125 measured soil available P, 31 measured soil total K, and 122 measured soil available K. Since some studies included more than one soil nutrient, the number of soil N, P, and K field experiments (459) was larger than that of total field experiments (132).

The environmental factors (climatic conditions, soil organic matter, and soil pH) and agricultural management practices (land use type, crops, straw type, initial C/N ratio) were selected to interpret the effects of SDMI on soil N, P, K. We categorized the climatic conditions into three groups, including northern temperate continental climate (NTC), northern temperate monsoon climate (NTM), and subtropical monsoon climate (STM). Each climate includes mean annual precipitation (MAP) and mean annual temperature (MAT). Land use types were grouped into dry land and paddy fields. Crops and straws were grouped into rice, wheat, maize, and rape. Soil pH was categorized as ≤6.5, 6.5–7.5, and >7.5. Initial C/N ratios of the applied straw plus fertilizer were calculated using Equation (1):

\[
InitialC/N\text{ratio} = \frac{S \cdot Cs}{(S \cdot Ns + Nf)}
\]

where \(S\) is the amount of applied straw \((g \text{ ha}^{-1})\), \(Cs\) is straw carbon concentration \((g \text{ kg}^{-1})\), \(Ns\) is straw nitrogen concentration \((g \text{ kg}^{-1})\), \(Nf\) is the amount of added inorganic N fertilizer \((g \text{ ha}^{-1})\). The C/N ratios were grouped into ≤15, 15–30, and >30 [23]. SOM was categorized as ≤20, 20–30, and >30 g kg\(^{-1}\) [24] (Table S2). Twenty-five provinces were included in the selected studies, mostly located in southeast China (Figure 1).

Figure 1. Spatial distribution of experimental sites from SDMI application compiled in meta-analysis.
2.2. Meta-Analysis

The meta-analysis was conducted via MATEWIN 2.1 (Rosenberg Software, Arizona State University, Tempe, AZ, USA). The effects of SDMI on soil N, P, K after straw returning were evaluated using Hedges’ d as shown by Equation (2) [25]. Hedges’ d was chosen in this study to calculate the effect size rather than the natural logarithm of the response ratio (RR) because the frequency distributions of soil N, P, K were more unimodal via Hedges’ d [26]:

\[
d = \frac{(X_e - X_c)}{S} J
\]

where \(d\) is the effect size of soil N, P, K; \(X_c\) and \(X_e\) denote the means of soil N, P, K in non-SDMI and SDMI treatments, respectively; and \(S\) and \(J\) are the pooled standard deviation and correction coefficient, respectively, calculated from the following equations:

\[
S = \sqrt{\frac{(Ne - 1)(Se)^2 + (Nc - 1)(Sc)^2}{3}}
\]

\[
J = \frac{3}{4(Nc + Ne - 2) - 1}
\]

where \(Sc\) and \(Se\) denote the standard deviations of soil N, P, K in non-SDMI and SDMI treatments, respectively; and \(Nc\) and \(Ne\) denote the sample size of soil N, P, K in non-SDMI and SDMI treatments, respectively. Data were extracted from the tables directly or extracted from the figures using GetData Graph Digitizer 2.24 software (Getdata Graph Digitizer, Fedorov S, Krasnoyarsk, Russia). The data not presented in the papers were requested from the authors. Gaussian distribution function was used to fit the normal distribution of the frequency distribution of each effect hedges’ d (Figure S2).

Publication bias was assessed using Funnel plots and Egger tests [27]. Rosenberg’s fail-safe-numbers (\(Nfs\)) were calculated to assess the robustness of soil N, P, K (Table S3) to the publication bias [28]. The results were considered robust despite the possibility of publication bias if \(Nfs > 5 * n + 10\), where \(n\) indicates the number of sizes. On condition that the standard deviations (SD) or standard errors (SE) were absent in the original reports, we used the approach outlined by “Bracken, 1992” to estimate SD [29].

To determine the impact of SDMI-amended straw on soil nutrients in relation to the different affecting factors (environmental factors and agricultural management practices), the heterogeneity of overall effect sizes between groups was tested using random-effect models. Each attribute (e.g., climatic conditions) was separated into different categories (e.g., northern temperate continental climate, northern temperate monsoon climate, and subtropical monsoon climate) to identify the significant differences among their effect sizes. For each categorical variable (climatic conditions, land use type, crops, straw type, initial C/N ratio, soil pH, and soil organic matter), total heterogeneity (\(Q_T\)) was partitioned into within-group (\(Q_W\)) and between-group (\(Q_B\)) variations. We determined the significance of the between-group heterogeneity (\(Q_B\)) using a randomization test [30] to understand whether the mean effect sizes of the categories differed between the levels of the factors. We used a chi-squared test to determine whether the remaining within-group heterogeneity (\(Q_W\)) was significant. The Q statistic follows a chi-square distribution with \(n-1\) degrees of freedom, where \(n\) is the number of paired observations between SDMI and non-SDMI treatments for a categorical variable. Categorical variables that were associated with low P values (\(p < 0.05\)) and large \(Q_B\) values are considered to have a better ability to predict the changes in the overall effect size (Table S4).

2.3. Statistical Analysis

A random-effects model was applied to assess the effects of SDMI-amended straw on soil N, P, K [31]. It was significantly positive or negative if the 95% confidence interval did not overlap with zero at a 0.05 level [25]. The difference in effect size between the two
categories was significant if 95% confidence intervals in the categories were not overlapping. Frequency distributions of the effect size were determined in SPSS11.0 (SPSS Inc., Chicago, IL, USA). Simple linear regression was used to analyze the relationship between the effect size on soil major nutrients and each quantifiable influencing factor, including climatic factors (i.e., mean annual precipitation (MAP), mean annual evaporation (MAE), and mean annual temperature (MAT)), initial C/N ratio, soil pH, and SOM. ArcGis 10.2 software (www.esri.com/en-us/arcgis, accessed on 1 January 2022) was used to identify the location of experimental sites included in our meta-analysis. If the latitude and longitude were not reported, they were estimated using the name and the location of the experimental site via the website https://www.findlatitudeandlongitude.com/, accessed on 1 January 2022 (Ashburn, VA, USA). Publication bias was tested using metafor [32], ggplot2 [33], and glmulti [34] packages in R. Meta-analysis and the assessment of between-group heterogeneity (QB) were performed in METAWIN 2.1 software (Rosenberg Software, Arizona State University, AZ, USA). The relative importance value for each variable was calculated as the sum of Akaike weights for all the models in which the variable was included. Such values can be considered as the overall support for each variable across all models. A cutoff of 0.8 was set to differentiate between important and non-essential predictors [35]. Simple linear regression models and all graphs were constructed in Origin 9.0 (Origin Lab Inc., Northampton, MA, USA).

3. Results
3.1. Changes in Soil Major Nutrients in Relation to the Application of SDMI-Amended Straw

Of all datasets, 257, 127, 105, 314, 93, and 318 reported total N, available N, total P, available P, total K, and available K, respectively. Overall, compared with straw incorporation alone, the application of SDMI-amended straw significantly increased soil total N (95% CI, 0.866 to 1.275), available N (95% CI, 0.653 to 1.175), total P (95% CI, 0.510 to 1.468), available P (95% CI, 0.636 to 0.928), total K (95% CI, 0.151 to 0.618), and available K (95% CI, 0.825 to 1.168) (Figure 2). Notably, SDMI led to a greater increase in soil total N than in total K, while no significant differences took place in the pairwise comparisons between total N and total P or between total P and total K, as well as among the available N, P, K concentrations (Figure 2). Furthermore, we compared the effects of SDMI on different forms of the same element. Our results revealed significant differences between total and available K ($p < 0.05$) (Figure 2c), while no significant differences occurred between the different N and P forms, respectively (Figure 2a,b).

![Figure 2](image-url). Effects of SDMI application on (a) soil total and available N, (b) total and available P, (c) total and available K, expressed as the mean effect size with bootstrap 95% confidence intervals. The number of observations for each category is given in parentheses. The differences between categories are significant if the probability level ($p$) is $<0.05$. The overall effect size is significantly positive or negative if 95% confidence interval does not overlap with zero at $p = 0.05$ level, and the difference in effect size between two categories is significant if 95% confidence intervals in the categories are not overlapping.
3.2. Effects of SDMI-Amended Straw on Soil Major Nutrients in Relation to the Environmental Factors

Figure 3 shows the effects of SDMI on soil major nutrients under different environmental factors. As can be seen, SDMI had significant impacts on soil N, P, K in the subtropical monsoon climate (STM) and northern temperate monsoon climate (NTM). In the northern temperate continental climate (NTC), SDMI had non-significant effects on soil total N (95% CI, −0.669 to 2.246), total P (95% CI, −2.886 to 1.693), available P, (−0.393 to 1.048), and total K (95% CI, −0.560 to 1.254), while its effects on available N (95% CI, 1.000 to 2.452) and available K (95% CI, 0.211 to 1.255) were all significant (p < 0.05). Except for total K, SDMI had significant effects on total and available nutrients in acid soils (pH ≤ 6.5) compared with the control (p < 0.05). In neutral soils (pH 6.5–7.5), the effects of SDMI on total and available nutrients were all significant (p < 0.05). In alkaline soils (pH > 7.5), only the changes in total P (95% CI, −1.198 to 1.046) and total K (95% CI, −0.356 to 1.159) were non-significant after SDMI application. Notably, SDMI had non-significant impacts on soil total N and available N at SOM ≤ 20 and 20–30 g kg⁻¹, respectively. The effect of SDMI on total N was significantly higher in alkaline soils (pH > 7.5) than in acid soils (pH ≤ 6.5) (p < 0.05). In addition, the effect size of SDMI on total K was larger in neutral soils (pH 6.5–7.5) than in acid soils (pH ≤ 6.5). Furthermore, SOM values >30 g kg⁻¹ had a significantly greater impact on SDMI functionality than those ≤30 g kg⁻¹ for total P (p < 0.05).

Figure 3. Effects of SDMI application on soil total N (a), available N (b), total P (c), available P (d), total K (e), and available K (f) under different environmental conditions, expressed as the mean effect size with bootstrap 95% confidence intervals. The number of observations for each category is given in parentheses. The differences between categories are significant if the probability level (p) is <0.05. The overall effect size is significantly positive or negative if 95% confidence interval does not overlap with zero at p = 0.05 level, and the difference in effect size between two categories is significant if 95% confidence intervals in the categories are not overlapping. NTC: northern temperate continental climate; NTM: northern temperate monsoon climate; STM: subtropical monsoon climate. SOM: soil organic matter content (g kg⁻¹).

3.3. Effects of SDMI-Amended Straw on Soil Major Nutrients in Relation to the Agricultural Management Practices

The effects of SDMI application on soil N, P, K under different agricultural management practices are shown in Figure 4. In accordance, SDMI significantly influenced soil N, P, K values compared with the control in paddy fields (p < 0.05). However, the effects of SDMI on soil total P (95% CI, −0.750 to 0.940) and total K (95% CI, −0.252 to 1.086) were non-significant in dry lands. As for the different crop types, compared with the control, the effects of SDMI on the different forms of soil N, P, K were all significant for maize and rice crops (p < 0.05). However, SDMI had non-significant effects on soil total P (95% CI, −0.144 to 1.105) under rape cultivation and on soil total N, P, K (95% CI, −0.426 to 1.649; 95% CI, −2.650 to 0.048; 95% CI, −0.908 to 0.125) as well as available K (95% CI, −0.015 to 0.773) under wheat cultivation. As for the different straw types, compared with the control, SDMI had significant effects on different forms of soil N, P, K for rice straw (p < 0.05). SDMI
had non-significant effects on soil total P and K for maize and wheat straws as well as on soil total K (95% CI, −0.120 to 0.776) for rape straw. Compared with the control, SDMI had significant effects on the different forms of soil N, P, K at initial C/N ratios ≤15 \((p < 0.05)\). Conversely, it had non-significant effects on soil available N (95% CI, −0.040 to 1.186) and total K (95% CI, −0.776 to 0.656) at initial C/N ratios of 15–30 and >30, respectively. It is worth mentioning that the response of soil total P to SDMI application was significantly greater under rice and maize cultivations than under wheat cultivation \((p < 0.05)\). The effect of SDMI on soil total K under maize cultivation was significantly higher than the other three crops, whereas the highest increase in available K was seen for rice \((p < 0.05)\).

In addition, SDMI had a significantly greater impact on soil total P at initial C/N ratios of 15–30 than ≤15 \((p < 0.05)\). Similarly, initial C/N ratios of 15–30 and >30 caused significant increases in the concentration of soil available K compared to the initial C/N ratios ≤15 after SDMI application \((p < 0.05)\).

**Figure 4.** Effects of SDMI application on soil total N (a), available N (b), total P (c), available P (d), total K (e), and available K (f) under different agricultural management practices, expressed as the mean effect size with bootstrapped 95% confidence intervals. The number of observations for each category is given in parentheses. The differences between categories are significant if the probability level \((p\) is <0.05. The overall effect size is significantly positive or negative if 95% confidence interval does not overlap with zero at \(p = 0.05\) level, and the difference in effect size between two categories is significant if 95% confidence intervals in the categories are not overlapping.

### 3.4. Changes in Soil Major Nutrients in Relation to the Integrated Effects of SDMI-Amended Straw and Affecting Factors

Based on our observations with the paired regulating variables, we explored the relative effects of multiple environmental factors and agricultural management practices on the responses of soil major nutrients to SDMI-amended straw. Accordingly, MAP was the best predictor of the effect of SDMI addition on soil total N, while other variables had negligible importance (Figure 5a). Specifically, the effect of SDMI-amended straw significantly decreased with MAP across sites \((R^2 = 0.025, P = 0.008;\) Figure 6a). Likewise, MAP was superior in predicting the effect of SDMI-amended straw on soil available N (Figure 5b). Correspondingly, linear regression analysis showed significant negative correlation between soil available N and MAP \((R^2 = 0.093, P = 0.0006;\) Figure 6b). The results of model-averaged of the summed Akaike weights revealed that SOM was the main regulator of the effect of SDMI-amended straw on soil total P (Figure 5c). From Figure 6c, a significant positive correlation appeared between SOM and soil total P \((R^2 = 0.042, P = 0.032)\). Model-averaged importance of the predictors’ analysis showed that the most important regulator of the effect of SDMI addition on soil available P was MAT, followed by MAP (Figure 5d). Conversely, MAT and MAP had no significant effects on the response of soil available P to SDMI-amended straw (Figure 6e,f). For soil total K, straw was the most important moderator (Figure 5e). MAP was also the best predictor of the effect of SDMI-amended straw on soil available K, followed by MAT (Figure 5f). In particular, the effect of SDMI on soil available K significantly increased with MAP \((R^2 = 0.010, P = 0.049;\) Figure 6e).
Figure 5. Model-averaged importance of the predictors for the effects of SDMI-amended straw on soil total N (a), soil available N (b), soil total P (c), soil available P (d), soil total K (e), and soil available K (f). SDMI: straw-decomposing microbial inoculant; MAT: mean annual temperature; MAP: mean annual precipitation; LUT: land use type; Straws: straw variety; Crops: crop variety. Cutoff is set at 0.8 (red solid line) to differentiate important from nonessential predictors.

Figure 6. Simple linear regression to investigate the integrated effects of SDMI application and environmental variables on soil total N (a), available N (b), total P (c), available P (d,e), and available K (f,g). MAP: mean annual precipitation; MAT: mean annual temperature. The n represent the samples of the regression.
4. Discussion

4.1. Changes in Soil Major Nutrients in Relation to the Application of SDMI-Amended Straw

Overall, the results of this meta-analysis revealed that SDMI-amended straw significantly increases soil N, P, K concentrations compared with non-SDMI-amended straw incorporation ($p < 0.05$) (Figure 2). These findings are consistent with the previous, less comprehensive reports [11,36,37]. This might be due to several reasons. First, upon arrival into the soil, the functional microorganisms of SDMI (i.e., yeasts, molds, bacteria, and bacillus) multiply in large numbers, and they secrete enzymes in high quantities to degrade cellulose, hemicellulose, and lignin, transforming straw N, P, K and other elements into the available forms [5,11,38,39]. Second, the contribution of SDMI to straw degradation requires N higher than that supplied by the straw. Hence, microbial straw decomposition may reduce the availability of N that is in or applied to the soil. Conversely, cellulose-decomposing bacteria can cause N fixation that, in turn, prevents the rapid transformation of chemical N fertilizer into NH$_4^+$ and NO$_3^-$ after returning SDMI-amended straw to the soil. This also prohibits ammonia volatilization and nitrate leaching, thus compensating and renewing soil N [40]. As a compound microbial agent, SDMI contains abundant active microorganisms increasing P and K solubilization/dissolution in the soil [37,41]. In addition, the SDMI’s organic matter-degrading agents can effectively improve the contents of soil N, P, K through the degradation of organic matter [39,42]. Another possible explanation is that a large number of functional microorganisms in SDMI might activate autochthonous biomass and enhance soil microbial functional diversity, resulting in higher amounts of endoenzyme in the viable microbial populations, and thus more enzyme accumulation in the soil. Soil enzyme activities are involved in nutrient cycling and organic matter decomposition, and they have a synergistic correlation with soil nutrients [5,11,43]. It is worth mentioning that SDMI application led to a significantly higher increase in soil total N/available K concentrations than total K. This might be due to the functional microorganisms of SDMI, inhibiting denitrification and reducing N losses by enhanced microbial N immobilization [44,45]. A significantly higher increase in soil available K than in soil total K might also contribute to the activity of several bacterial and fungal communities of SDMI, solubilizing the precipitated K into available forms [46,47].

4.2. Effects of SDMI-Amended Straw on Soil Major Nutrients in Relation to the Environmental Factors

Our results showed that various environmental factors have different impacts on the effect of SDMI on soil N, P, K concentrations (Figure 3). For instance, compared with NTC climate, the application of SDMI-amended straw caused higher increases in the different forms of soil N, P, K in STM and NTM climates due to their higher soil temperature and moisture, increasing the microbial activity of SDMI and promoting the release of straw nutrients [48,49]. The consistent changes in soil N, P, K concentrations after SDMI application in neutral soils compared to acid and alkaline soils can be explained by the higher colonization of non-indigenous straw decomposing microorganisms in neutral soils [50]. Interestingly, only the effect of SDMI-amended straw on soil available N was non-significant in soils with moderate SOM concentrations of 20–30 g kg$^{-1}$ (Figure 3b). Moderate fertility conditions, favoring the survival and activity of microorganisms, accelerate the decomposition and transformation of straw, increasing the absorption/utilization of soil available N by plants [38,51]. SDMI application caused the highest increase in soil total P at SOM concentrations of $\leq$20 g kg$^{-1}$, which was further justified by the significant correlation between SOM and soil total P after SDMI application ($P < 0.05$) (Figure 5c).

4.3. Effects of SDMI-Amended Straw on Soil Major Nutrients in Relation to the Different Agricultural Management Practices

The higher increases in soil N, P, K concentrations in paddy fields compared to dry land fields after SDMI application might be due to the higher decomposition of organic matter in paddy soils to compensate the low energy in anaerobic condition (Figure 4) [52].
From Figure 4, various crops had different effects on the levels of soil nutrients. In particular, SDMI-amended straw had non-significant and significant effects on soil total P and soil available P under rape cultivation, respectively ($p < 0.05$). This may contribute to the high P demand of rape, converting insoluble P forms into available forms by SDMI, an exogenous bacterium [53]. Non-significant effects of SDMI on soil total N, P, K, as well as on available K under wheat cultivation might contribute to the low temperature of its growing season (winter), inhibiting SDMI activity [48,49]. Furthermore, wheat has a stronger ability to uptake K than maize [54,55]. Significant increases occurred in total P of soils used for maize and rice cultivation, which might contribute to their lower P demand/uptake than wheat [56]. Correspondingly, maize and rice plants have lower K demand than wheat, resulting in a significantly higher accumulation of total and available K in maize and rice soils ($p < 0.05$) (Figure 4) [57,58]. Besides, anaerobic redox condition is one of the most important factors for higher P availability in paddy soils [59,60].

Various straw types also had different effects on the levels of soil nutrients (Figure 4). Non-significant effects of SDMI on total P and K of maize and wheat straw-amended soils might be due to the slow decomposition rate of straw [61,62], while non-significant effects of SDMI on soil total K of rape straw-amended soils might contribute to the thick cuticle layer of the outer surface of rape straw, which is not easily biodegradable [63].

Generally, higher initial C/N ratios led to a significantly higher accumulation of total and available forms of soil nutrients ($p < 0.05$) (Figure 4). This is most likely the result of the stimulation of soil microbial respiration, decomposition, and biomass with increasing initial C/N ratio [64–66]. Nevertheless, no significant increases occurred in the concentration of soil available N at the initial C/N range of 15–30 g kg$^{-1}$, which might be due to the short-term accelerated plant N removal after SDMI application [67].

4.4. Correlations between the Effects of SDMI-Amended Straw on Soil Major Nutrients and Influencing Factors

The model average of the summed Akaike weights indicated that the climatic factors had major impact on the levels of soil nutrients after the application of SDMI-amended straw (Figure 5). Of all factors, MAP was the best predictor of the effect of SDMI addition on soil total and available N (Figure 5a,b). Specifically, MAP had a significant negative correlation with the changes in soil total and available N after SDMI application (Figure 6a,b). This might contribute to the enhancement of denitrification by the functional microorganisms with increasing the precipitation [68]. Meanwhile, higher precipitation can increase N leaching [68]. Furthermore, SOM was the most important variable to predict the effect of SDMI addition on soil total P (Figure 5c), as justified by their significant positive correlation (Figure 6c). This might contribute to SOM decomposition, releasing P for microorganisms [69]. As shown by the regression analysis, MAP was the best predictor of the effect of SDMI addition on soil available K, followed by MAT (Figure 5f; Figure 6f). Straw K mainly exists in the ionic state. Thus, SDMI can enhance straw K dissolution with increasing precipitation, resulting in higher content of soil available K [70].

4.5. Study Limitations

To the best of our knowledge of the literature review, there are three other issues that may influence the findings of this study. First, existing studies have not investigated the effects of SDMI on soil major nutrients in relation to: (a) the microbial composition and amount of SDMI, (b) soil texture, and (c) the amount of straw. However, the data for these metrics are not included in our compiled database, as most case studies did not provide the information on them. Hence, future works should consider these variables to eliminate the uncertainties in our interpretations. Second, changes in soil major nutrients in relation to SDMI application are partly regulated by the management of straw application and incorporation (e.g., straw mulching and/or a buried straw layer). Despite its importance, most papers did not report the specific method of straw returning. Hence, we were unable to associate the changes in soil major nutrients with the various methods of straw returning.
To overcome these shortcomings, workers should include more straw returning methods data of soil N, P, K, leading to a more comprehensive assessment of the effects of SDMI application on soil major nutrients. Additionally, given that agricultural management practices directly affect the straw decomposition and nutrient release at the regional scales, it is also important that future studies explore the impact of SDMI on soil major nutrients in micro-climatic conditions.

5. Conclusions

Using a meta-analysis, the present study suggested that the SDMI application generally increases soil total and available N, P, K concentrations compared with non-SDMI-amended soils. We also identified MAP as the key environmental factor influencing the impact of SDMI addition on soil total N, available N, and available K. For soil total P, SOM was the main factor regulating the effect of SDMI application. Our results revealed that STM and NTM had greater impacts on soil functional N than NTC ($p < 0.05$). Notably, SDMI had non-significant impact on the available N at SOM 20–30 g kg$^{-1}$. Interestingly, under wheat cultivation, SDMI caused no significant changes to soil total N, P, K contents; while it had significant effects on soil available N, P, K forms. In addition, the effects of SDMI on soil N, P, K were all significant under both rice cultivation and rice straw returning ($p < 0.05$).

Overall, this meta-analysis study suggested the application of SDMI-amended rice straw with an initial C/N ratio of ≤15 to neutral soils in temperate and subtropical monsoon climates as a promising strategy to maximize the concentrations of both soil total and available N, P, K contents. Based on the SDMI application to agricultural soils, our findings reveal major implications for the development of straw returning strategies. Further studies should include more factors (e.g., soil texture, the amount of straw, and straw returning method) and the mechanisms that regulate the effects of SDMI on soil major nutrients.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12040890/s1, Figure S1: A PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram to illustrate the systematic search strategy and the process of study selection. Where n is the number of studies; Figure S2: Frequency distributions of effect size for the responses of soil total N(a), total P (b), total K (c), available N (d), available P (e), and available K (f) to SDMI-amended straw. The solid curve is a Gaussian distribution fitted to the frequency data. n indicates the number of observations; Table S1: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist; Table S2: Number of samples for different climatic conditions, land use types, crops, straws, initial C/N ratios, soil pH, and soil organic matter included in this study; Table S3: Exploring potential publication bias and robustness of models by Egger tests and Rosenberg’s fail-safe-numbers (Nfs); Table S4: Relationships between the effect sizes of SDMI on soil N, P, K relative to climate region, soil pH, soil initial SOM, land use type, crop type, straw type, soil initial C/N. Statistical results from random-effects meta-analysis were reported as between-group heterogeneity ($Q_B$), within-group heterogeneity ($Q_W$), and total heterogeneity ($Q_T$) in effect sizes among studies (n). * $p < 0.05$; ** $p < 0.01$; Database: The information collected in the database is related to the basic information of the study, the date of meta-analysis date, relative importance analysis, and linear regression analysis data involved in the study.

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