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Effects of Rice Straw Combined with Inorganic Fertilizer on Grain Filling and Yield of Common Buckwheat

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Abstract: This study aims to clarify the effect of rice straw combined with inorganic fertilizer on the grain-filling characteristics and yield formation of common buckwheat (*Fagopyrum esculentum* Moench) and provide a scientific basis for straw fertilizer utilization and the scientific fertilization of common buckwheat in Guizhou Province.Common buckwheat 'Fengtian1' was field-grown and treated with no straw and no fertilization (CK), no straw with normal fertilizer (SF), full straw with 20% reduction in conventional fertilization (SH), full straw with 40% reduction in conventional fertilization (SM), full straw with 80% reduction inconventional fertilization (SL), and full straw with no fertilization (HT). The results showed that the initial growth power (R_0), maximum and average grain-filling rate, and starch synthase activity of the superior grains were higher than those of the inferior grains. Compared with CK, the treatments with straw and inorganic fertilizers remarkably increased the contents of available nitrogen, available potassium, available phosphorus, and organic matter in the rhizosphere of common buckwheat. SH and SF treatments remarkablyimproved the fertilizer contribution rate and fertilizer agronomic utilization rate, promoted root growth, and enhanced the starch branching enzyme and soluble starch synthase activities of superior and inferior grains. Compared with CK, SH treatment considerably increased the number of grains per plant, grain weight per plant, 100-grain weight, and final yield. Thus, straw combined with inorganic fertilizers, particularlythe SH treatment, should be recommended as an agronomic method for promoting grain filling and increasing the yield of common buckwheat.

Keywords: common buckwheat; rice straw; fertilizer application reduction; grain filling; yield

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1. Introduction

Common buckwheat (*Fagopyrum esculentum* Moench), which belongs to genus *Fagopyrum* Mill [1,2], is mainly cultivated in Russia, China, Ukraine, France, Korean, Kazakhstan, Pakistan, Poland, and Japan [3]. Compared with the major grain crops, such as rice, maize, and wheat, common buckwheat has a short growth period, rapid growth, and wide adaptability. In addition, it contains abundant functional components, such as flavonoids and dietary fiber, which have provided many medicinal and nutritional values [4,5].

As a strategic material for national food security, fertilizer is the material basis for the realization of sustainable agricultural development [6]. Excessive fertilizers have been applied to farmlands to obtain higher crop yields and meet people's demand for food [7]. However, the heavy application of inorganic fertilizers has caused various negative impacts on farmland ecosystems, such as a greenhouse effect, water eutrophication, the increase of insect pests, etc. [8]. Therefore, reducing the amount of inorganic fertilizers and replacing inorganic fertilizers with organic fertilizers have become necessary measures to develop sustainable agriculture. China is a large agricultural country, and a large amount of crop straws are produced every year. Straw application can alleviate the environmental pollution caused by straw waste and incineration, realize optimal resource allocation, improve the physical and chemical properties of soil, improve the quality of soil fertility, promote crop growth, and achieve high and stable yield of food crops [9,10]. Our team previously studied the effect of different crop straw (such as corn, rice, rapeseed, and wheat) on the yield of common buckwheat and found that the yield of wheat and rice straw treatment were higher, which were 2.32 and 2.28 times that of no straw treatment, respectively [11]. However, the carbon-to-nitrogen ratio of cereal crop straw is usually higher than that of soil. In the early stage of returning straw to the field, straw decomposition will consume soil-available nitrogen and therefore affect the growth of crop seedlings and result in yield reduction [12,13].

Straw combined with inorganic fertilizer can improve or maintain soil fertility while ensuring crop yield [14]. Chen et al. [15] found that compared with the single application of inorganic fertilizer, the combination of straw and inorganic fertilizer remarkably improves soil fertility and increases soil enzyme activity. Lu et al. [16] found that reducing the inorganic fertilizer by 30% and applying organic fertilizer while the full amount of straw to the field can improve the grain yield under the rice-wheat rotation system. However, relevant research on the effect of straw combined with inorganic fertilizer on the growth and yield formation of common buckwheatis lacking.

Therefore, the locally popular cultivar of common buckwheat in Guizhou Province, namely, Fengtian 1 (FT1), was used as the test material and treated with six different treatments. The major objective was to reveal the effects of rice straw combined with inorganic fertilizer on: (1) grain filling of superior and inferior grains, (2) available nutrients in the rhizosphere, and (3) the yield formation of common buckwheat. The results provide a novel agronomic method for scientific and efficient fertilization under straw and a high-yield cultivation technique for common buckwheat.

2. Materials and Methods

2.1. Plant Materialsand Growth

FT1, a locally cultivated cultivar of common buckwheat in Guizhou Province, China, was provided by the Buckwheat Industry Technical Research Center of Guizhou Normal University, China.

The experiment was initiated during the common buckwheat growing season (August–October) from 2020 to 2021 at Xiaba's Cultivation Experiment Station of the Key Laboratory for Cultivation Physiology and Application of Buckwheat of Guizhou (1250 m, 106.95° E, 26.72° N), Guiyang City, Guizhou Province, China. The soil used was xanthic ferralsols with 40.01 mg kg^{-1} available phosphorus, 59.61 mg kg^{-1} available potassium, 17.42 mg kg^{-1} available nitrogen, and 7.07 g kg^{-1} organic matter. Soil nutrient contents were determined using a multichannel intelligent soil nutrient meter (OK-V24, China).

The experiment was conducted using a single-factor randomized block design with three replicates. The area of each test plot was 2 m $\times$ 4 m, and plots were separated by a30cmwidegap that was wrapped with agricultural film to prevent water and fertilizer leakage. Six treatments were set up in this experiment: no straw with no fertilization (CK), no straw with normal fertilizer (SF), full straw with 20% reductionin conventional fertilization (SH), full straw with 40% reduction in conventional fertilization (SM), full straw with 80% reduction in conventional fertilization (SL), and full straw with no fertilization (HT). The inorganic fertilizer (compound fertilizer, N:P:K = 15:15:15) concentration is 600 kg·hm^{-2} for high yield in Guizhou [17], and the total amount of full rice straw is 9000 kg·hm^{-2} [11]. Inorganic fertilizer was applied as the base fertilizer once, and no fertilizer was applied throughout the growth period. Rice straw was crushed into about 3 cm by a pulverizer, then directly mulched and applied to the field. Seeds were sown in the plot on 12 August 2020 and 16 August 2021. The row spacing and planting density were 33 cm and 5.25 g m^{-2} (approximately 90–100 plants per m^2). Seeds were harvested (70% of seeds turned black) on 10 October 2020 and 12 October 2021. Normal agricultural practices were implemented. The mean monthly temperature, monthly sunshine duration, and rainfall during the experiment are shown in Table 1; the weather station is about 4.2 km away from the trial site.

Table 1. Mean temperature and mean sunshine hours during the growing year of common buckwheat.

Month	Mean Temperature (°C)		Mean Sunshine Hours (h)		Mean Rainfall (mm)	
	2020	2021	2020	2021	2020	2021
August	23.81	23.20	184.2	171.5	50.7	112.4
September	18.76	22.75	55.5	182.2	142.6	125.6
October	14.24	17.23	99.3	88.6	87.4	98.3

The data comes from the National Meteorological Science Data Center of China (http://data.cma.cn accessed on 22 February 2022).

2.2. Sample Preparation

The plants with uniform growth and without diseases and insect pests were selected from the plots of each treatment. At the beginning of the flowering period, approximately 1200–1500 flowers that bloomed on the same day were marked on the calyx with a brush dipped in black ink. After 5 days, the marked flowers were sampled for the first time and every 5 days until maturation. The superior and inferior grains of common buckwheat were divided according to the results of an earlier study [18]: the grains on nodes 1–3 above the branch nodes from the main stem were the superior grains, whereas those on the secondary branches at the base were the inferior grains.

Samples from each treatment were collected at 5, 10, 15, 20, and 25 days after marking the flowers. A total of 200 seeds were collected from the superior and inferior grains, among which 150 grains were divided into three portions, and the 100-grain weight was calculated after drying for analysis of the grain-filling characteristics. The remaining 50 fresh grains were frozen in liquid nitrogen for 30 s and then stored in a −80 °C refrigerator for the determination of starch synthase activity in the grains.

The rhizosphere of approximately 10–15 plants for each plot with uniform growth was sampled at the maturity period of common buckwheat. The sampled rhizosphere of every treatment was dried to constant weight with natural air drying for measuring soil available nutrient and pH [19].

Approximately 10 plants with uniform growth from each plot were sampled with complete roots at the seedling, flowering, grain filling, and maturity periods of common buckwheat.

2.3. Determination

2.3.1. Grain-Filling Performance

In accordance with Zhu et al. [20], Richards' equation was used to describe the grain-filling process: $W = A/(1 + Be^{-Kt})\ 1/N$, where W is the grain weight of common buckwheat during grain filling, A is the final grain weight upon harvest, B is the initial value of the parameter, e is a constant, K is the constant growth rate, N is the shape parameter, and t is the time after flowering.

2.3.2. Starch Synthase Enzyme Activity in the Grains

Soluble starch synthase (SSS) activities in the superior and inferior grains were determined using the method of Yang et al. [21]. Starch-branching enzyme (SBE) activities were determined with reference to Nakamura and Yuki [22].

2.3.3. Rhizosphere-Available Nutrient and pH

The contents of available nitrogen, available phosphorus, available potassium, and organic matter in the rhizosphere were determined by a multichannel intelligent soil nutrient analyzer (OK-V24) according to the method of Zhang et al. [19]. In accordance with Zhang et al. [19], the pH value of the rhizosphere was determined by a pH instrument (MP511), andsoil moisture content was determined by a soil moisture meter (TZS-2X).

2.3.4. Root Morphology

The roots of common buckwheat were cleaned with running water and carefully unfolded with tweezers so that the roots did not overlap. Based on the method of Wang et al. [23], all roots were scanned using a root scanner (GXY-A, Zhejiang Tuopu Instrument Co., Ltd., Hangzhou, China). In accordance with Zhang et al. [19], total root length, surface area, volume, and mean diameter were obtained using the root analysis system WinRHIZO (version 4.0b, Regent Instruments, Inc., Quebec City, QC, Canada).

2.3.5. Agronomic Characteristics, Yield, and Fertilizer-Use Efficiency

Based on the method of Zhang et al. [19], plant height, main stem branch number, main stem node number, grain weight per plant, grain number per plant, and 100-grain weight were determined. Based on the method of Song et al. [17], the seeds of the whole plot of common buckwheat were artificially harvested, when at least 70% grains were mature. The yield was presented as yield per hectare, and grain yield expressed at less than 13%moisture content. The method of Lu et al. [16] was used to calculate the fertilizer utilization rate.

Fertilizer contribution rate = (grain yield in fertilizer application plots − grain yield in fertilizer omission plots)/grain yield in fertilizer application plots × 100%

Fertilizer agronomic utilization rate = (grain yield in fertilizer application plots − grain yield in fertilizer omission plots)/fertilizer application rate

2.4. Statistical Analyses of Experimental Data

The data were processed using Microsoft Excel 2003 and SPSS22.0. A two-way ANOVA was performed, and means were tested by least significant difference at p = 0.05 (LSD 0.05).

3. Results

3.1. Grain-Filling Characteristics of Common Buckwheat

The determination coefficient (R^2) of each curve equation ranged from 0.939 to 0.991, which indicate that fitting the filling process of common buckwheat with Richards' equation is feasible (Table 2). The final growth value (A) of superior grains was the highest in the SH treatment, followed by that in the SF treatment, whereas the A value of inferior grains was the highest in the SF treatment. The initial filling power (R_0) was the lowest in the superior and inferior grainsin the CK treatment and the highest in the superior grains treated with SH and SF and the inferior grains treated with SF. The R_0 of the superior grains was higher than that of the inferior grains. The time to reach the maximum filling rate ($T_{max.G}$) of the superior and inferior grains of common buckwheat was the longest in the CK treatment. $T_{max.G}$ was the shortest in the superior grains under the SH treatment, and theinferior grains under the SF treatment. The $T_{max.G}$ of theinferior grains was longer than that of the superior grains. Maximum grain-filling rate (G_{max}) and average grain-filling rate (G_{mean}) were the highest in superior grains under the SH treatment andinferior grains under the SF treatment. The G_{max} and G_{mean} of the superior grains were higher than those of the inferior grains. The results in 2020 and 2021were similar.

Table 2. Effect of rice straw combined with inorganic fertilizer on grain-filling parameters.

Year	Grain Position	Treatment	A	B	K	N	R^2	R_0	$T_{max.G}$ (d)	G_{max} g(100d)$^{-1}$	G_{mean} g(100d)$^{-1}$
2020	Superior grains	CK	3.705 b	0.255 a	0.180 ab	0.046 a	0.9994 a	1.668 f	9.304 a	1.393 ab	0.163 b
		SF	3.993 ab	0.126 a	0.168 ab	0.046 a	0.9985 a	7.119 a	8.869 a	1.489 ab	0.165 b
		SH	4.106 a	0.490 a	0.191 ab	0.072 a	0.9991 a	3.105 c	8.062 a	1.562 a	0.189 a
		SM	4.101 a	0.246 a	0.148 b	0.056 a	0.9959 b	1.916 e	9.786 a	1.537 a	0.152 b
		SL	3.700 b	0.218 a	0.248 a	0.040 a	0.9990 a	2.871 d	9.515 a	1.328 b	0.162 b
		HT	3.810 ab	0.338 a	0.214 ab	0.049 a	0.9995 a	4.834 b	8.852 a	1.436 ab	0.199 a

Table 2. *Cont.*

Year	Grain Position	Treatment	*A*	*B*	*K*	*N*	R^2	R_0	$T_{max.G}$ (d)	G_{max} g(100d)$^{-1}$	G_{mean} g(100d)$^{-1}$
2020	Inferior grains	CK	3.217 a	1.378 a	0.196 a	0.145 a	0.9975 a	0.779 d	10.609 a	1.261 c	0.146 ab
		SF	3.402 a	0.918 a	0.195 a	0.156 a	0.9994 a	1.917 a	9.095 b	1.491 a	0.148 ab
		SH	3.355 a	2.528 a	0.209 a	0.270 a	0.9998 a	0.908 c	10.168 ab	1.384 a	0.155 a
		SM	3.224 a	1.031 a	0.185 a	0.147 a	0.9997 a	1.460 b	9.874 ab	1.265 c	0.138 b
		SL	3.226 a	1.781 a	0.188 a	0.190 a	0.9994 a	0.903 c	9.837 ab	1.284 c	0.137 b
		HT	3.255 a	2.820 a	0.219 a	0.252 a	0.9978 a	1.412 b	9.931 ab	1.327 b	0.157 a
2021	Superior grains	CK	3.638 bc	0.985 a	0.274 b	0.1015 b	0.991 a	2.695 b	8.308 a	1.404 b	0.237 b
		SF	4.038 b	0.982 b	0.278 a	0.1017 a	0.965 ab	2.733 a	8.150 b	1.558 ab	0.267 ab
		SH	4.150 a	0.982 b	0.278 a	0.1017 a	0.990 a	2.734 a	8.147 b	1.601 a	0.275 a
		SM	3.821 bc	0.983 b	0.276 ab	0.1016 ab	0.940 b	2.719 ab	8.207 b	1.474 ab	0.251 ab
		SL	3.586 c	0.984 ab	0.275 b	0.1015 b	0.952 b	2.705 b	8.265 ab	1.383 b	0.232 b
		HT	3.786 bc	0.983 b	0.277 ab	0.1017 a	0.939 b	2.721 ab	8.120 b	1.461 ab	0.249 ab
	Inferior grains	CK	3.299 b	0.987 a	0.270 b	0.1012 b	0.945 a	2.662 b	8.450 a	1.273 b	0.212 b
		SF	3.675 a	0.984 b	0.275 a	0.1016 a	0.953 a	2.708 a	8.249 b	1.418 a	0.241 a
		SH	3.512 ab	0.985 ab	0.273 ab	0.1014 ab	0.964 a	2.688 ab	8.335 ab	1.355 ab	0.228 ab
		SM	3.507 ab	0.985 ab	0.273 ab	0.1014 ab	0.949 a	2.688 ab	8.340 ab	1.333 ab	0.228 ab
		SL	3.368 b	0.987 ab	0.271 b	0.1013 b	0.960 a	2.671 b	8.412 ab	1.299 b	0.217 b
		HT	3.624 ab	0.984 b	0.294 ab	0.1015 ab	0.941 a	2.702 ab	8.276 b	1.398 ab	0.237 ab

Note: Small letter in the same column means a significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reduction in conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization. *A*: the final growth value; *B*: the initial value of parameter; *K*: the constant growth rate parameter; *N*: the shape parameter, R^2: the determination coefficient; R_0: the initial filling power; $T_{max.\ G}$: the time to reach the maximum filling rate; G_{max}: the maximum filling rate; G_{mean}: the mean filling rate.

3.2. Starch Synthase Enzyme Activity in Superior and Inferior Grains

The SSS and SBE activities in superior and inferior grains increased initially and then decreased with the advancing growth period (Table 3). The SSS and SBE activities reached the maximum at 15 days after anthesis for superior grains and 20 days after anthesis for inferior grains. The SSS activity of superior grains at 25 days after anthesis was the highest in the SF treatment, followed by the SH treatment. In comparison, the SSS activity of the superior grains at the other periods was the highest in the SH treatment, followed by the SF treatment. The SSS activity of the inferior grains was the highest in the SH treatment. The SBE activity of the superior grains was the highest in the SF treatment, followed by the SH treatment, whereas the SBE activity of inferior grains was the highest in the SH treatment, followed by the SF treatment. The SSS and SBE activities of the superior grains were remarkably higher than those of the inferior grains. The results in 2020 and 2021 were similar.

Table 3. Effect of rice straw combined with inorganic fertilizer on starch synthase activity.

Year	Item	Grain Position	Treatment	Period				
				5d	10d	15d	20d	25d
2020	Soluble starch synthase (SSS, U mg^{-1} min^{-1})	Superior grains	CK	2.68 c	3.54 e	3.91 c	3.17 c	2.73 c
			SF	4.48 a	4.73 b	5.54 a	4.63 a	4.52 a
			SH	3.34 b	3.77 d	5.27 a	4.55 a	4.48 a
			SM	3.63 b	3.83 d	4.49 b	3.48 b	3.15 b
			SL	3.40 b	4.15 c	4.81 b	3.20 c	3.18 b
			HT	4.50 a	5.15 a	5.67 a	4.66 a	4.58 a
		Inferior grains	CK	1.70 d	1.78 cd	2.31 f	2.01 d	1.83 e
			SF	2.98 a	3.44 a	4.92 b	3.88 a	3.53 a
			SH	2.72 b	2.69 b	3.40 d	2.50 b	2.15 c
			SM	1.37 e	1.44 d	4.37 c	2.37 c	2.09 d
			SL	1.10 f	2.11 c	2.79 e	2.62 b	2.57 b
			HT	2.13 c	2.98 ab	5.31 a	3.83 a	3.58 a

Table 3. *Cont.*

Year	Item	Grain Position	Treatment	Period				
				5d	10d	15d	20d	25d
2020	Starch-branching enzyme (SBE, U g^{-1} min^{-1})	Superior grains	CK	2.16 e	3.85 d	5.56 e	4.13 c	3.35 e
			SF	3.27 b	5.84 a	6.75 c	5.13 a	4.66 a
			SH	2.66 cd	5.39 b	5.93 d	5.27 a	4.35 b
			SM	2.51 d	5.16 c	7.08 b	5.20 a	4.16 c
			SL	2.64 c	5.56 b	6.74 c	4.86 b	3.50 d
			HT	3.98 a	5.77 a	7.74 a	5.28 a	4.61 a
		Inferior grains	CK	1.73 e	2.43 d	3.55 e	3.84 e	3.10 c
			SF	2.82 a	3.17 ab	4.03 b	4.75 c	4.02 a
			SH	2.64 b	3.21 ab	4.04 b	4.73 cd	3.29 b
			SM	2.49 c	3.06 bc	3.94 c	4.93 b	3.53 b
			SL	1.95 d	2.98 c	3.84 d	4.71 d	3.23 b
			HT	2.79 a	3.29 a	4.23 a	5.13 a	4.15 a
2021	Soluble starch synthase (SSS, U mg^{-1} min^{-1})	Superior grains	CK	3.22 b	5.49 f	6.84 e	5.75 e	4.62 d
			SF	3.74 ab	6.37 b	8.15 b	6.65 b	6.16 a
			SH	3.86 a	7.14 a	8.42 a	7.75 a	5.26 b
			SM	3.33 b	5.75 d	7.86 c	6.68 b	4.86 c
			SL	2.95 c	5.56 e	6.47 f	6.32 c	5.15 b
			HT	3.68 ab	6.03 c	7.52 d	6.02 d	5.19 b
		Inferior grains	CK	1.39 c	2.08 e	5.64 c	5.67 d	4.57 c
			SF	1.63 b	3.43 d	5.35 d	5.53 d	4.18 e
			SH	1.96 a	4.76 a	6.07 a	7.22 a	5.13 a
			SM	1.28 d	4.47 b	4.31 f	6.53 b	3.71 f
			SL	0.98 e	3.42 d	5.84 b	6.08 c	4.72 b
			HT	0.95 e	3.57 c	4.68 e	5.34 e	4.25 d
	Starch-branching enzyme (SBE, U g^{-1} min^{-1})	Superior grains	CK	4.26 f	7.54 d	9.95 d	8.36 d	4.06 e
			SF	6.16 a	11.21 a	12.69 a	10.49 a	7.29 a
			SH	6.06 b	8.57 b	11.67 b	9.16 b	6.90 b
			SM	5.83 d	8.46 b	11.61 b	8.54 c	6.38 c
			SL	5.06 e	8.28 c	10.03 d	9.14 b	5.66 d
			HT	5.96 c	8.51 b	10.74 c	8.06 e	4.06 e
		Inferior grains	CK	2.97 b	3.58 e	4.94 e	6.48 f	3.11 f
			SF	3.89 ab	5.21 b	6.68 b	8.30 b	4.63 b
			SH	3.98 a	5.93 a	7.57 a	8.81 a	4.84 a
			SM	3.17 b	5.05 c	6.45 d	7.43 c	4.27 c
			SL	2.80 b	4.09 d	6.52 c	7.02 d	3.91 d
			HT	2.55 c	3.36 f	4.83 f	6.62 e	3.75 e

Note: Small letter in the same column means significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reductionin conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization.

3.3. Rhizosphere Available Nutrient and pH

Compared with CK, straw combined with inorganic fertilizer considerably increased the contents of available nitrogen, available potassium, available phosphorus, and organic matter in the rhizosphere of common buckwheat (Table 4). The content of available nitrogen in the SF treatment was substantially higher than those in the other five treatments, the contents of available potassium and available phosphorus in the SM treatment were considerably higher than those in other treatments, and the contents of organic matter in the SL and HT treatments were remarkably higher than those in other treatments. No statistical differences in pH value were found among the treatments. The water content in the CK treatment was remarkably lower than those of the other five treatments. The results in 2020 and 2021were similar.

Table 4. Effect of rice straw combined with inorganic fertilizer on soil available nutrient.

Year	Treatment	Available Nitrogen (mg kg^{-1})	Available Potassium (mg kg^{-1})	Available Phosphorus (mg kg^{-1})	pH	Organic Matter (g kg^{-1})	Water Content (%)
2020	CK	21.94 f	55.69 f	54.84 f	6.90 a	6.90 f	0.24 c
	SF	45.79 a	116.04 c	60.82 e	6.82 a	7.95 d	0.30 b
	SH	26.74 e	76.81 e	67.13 b	6.85 a	8.04 c	0.37 a
	SM	32.12 c	156.13 a	70.26 a	6.83 a	7.48 e	0.31 b
	SL	28.91 d	115.29 c	66.03 c	6.90 a	9.13 a	0.33 b
	HT	41.71 b	135.35 b	62.47 d	6.89 a	8.37 b	0.29 b
2021	CK	24.63 f	81.20 f	62.81 f	6.78 a	6.10 e	0.21 b
	SF	69.65 a	100.68 d	70.03 e	6.81 a	6.72 d	0.28 a
	SH	58.50 b	193.69 b	71.55 d	6.79 a	7.70 b	0.36 a
	SM	27.80 e	242.44 a	91.84 a	6.79 a	7.39 c	0.29 a
	SL	32.72 d	85.83 e	85.89 b	6.87 a	7.94 a	0.28 a
	HT	35.71 c	150.52 c	79.04 c	6.78 a	7.81 a	0.27 a

Note: Small letter in the same column means significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reduction in conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization. pH: potential of hydrogen.

3.4. Root Morphology

The root length, root surface area, root volume, and root mean diameter of FT1 showed a continuously increasing trend with the advancement of the growth period (Table 5). Root length, root surface area, root volume, and root mean diameter were the largest under the SH treatment at the seedling and flowering stages and reached the maximum under the SF treatment at the grain filling and mature stages. The results in 2020 and 2021were similar.

Table 5. Effect of rice straw combined with inorganic fertilizer on the root morphology.

Year	Item	Treatment	Period			
			Seedling Stage	Anthesis Stage	Grain-Filling Stage	Mature Stage
2020	Root length (cm)	CK	22.94 d	40.60 d	63.28 e	107.97 b
		SF	39.37 a	65.02 b	101.23 a	173.31 a
		SH	41.13 a	89.02 a	102.47 a	151.29 ab
		SM	32.45 b	51.17 c	70.02 d	135.74 ab
		SL	29.63 c	64.13 b	92.65 b	140.25 ab
		HT	28.43 c	41.85 d	80.68 c	116.92 b
	Root Surface area (cm^2)	CK	5.34 d	12.67 c	13.67 c	32.19 b
		SF	8.99 b	26.91 a	31.08 a	71.76 a
		SH	12.03 a	27.62 a	35.52 a	68.95 a
		SM	8.98 b	26.48 a	34.19 a	46.77 ab
		SL	8.65 b	11.61 c	30.35 a	62.08 a
		HT	7.00 c	19.04 b	22.79 b	34.20 b
	Root volume (cm^3)	CK	0.15 c	0.46 c	1.03 e	2.34 c
		SF	0.31 b	0.56 c	1.84 b	4.77 b
		SH	0.47 a	1.66 a	2.07 a	5.96 a
		SM	0.24 bc	1.18 b	1.51 c	2.32 c
		SL	0.29 bc	1.62 a	1.93 a	2.22 c
		HT	0.16 bc	0.98 b	1.25 d	2.29 c
	Root average diameter (mm)	CK	0.64 b	0.85 a	0.85 b	0.99 c
		SF	0.80 ab	0.87 a	1.00 ab	1.51 a
		SH	0.94 a	0.99 a	1.07 a	1.53 a
		SM	0.85 ab	0.90 a	0.96 ab	1.17 bc
		SL	0.69 b	0.81 a	0.91 b	1.28 b
		HT	0.74 b	0.87 a	0.98 ab	1.03 c

Table 5. *Cont.*

Year	Item	Treatment	Period			
			Seedling Stage	Anthesis Stage	Grain-Filling Stage	Mature Stage
2021	Root length (cm)	CK	35.68 c	50.34 b	60.18 f	89.56 b
		SF	28.24 c	53.14 b	138.13 a	172.18 a
		SH	56.64 a	87.32 a	125.44 b	127.23 ab
		SM	32.72 c	86.89 a	91.11 c	160.06 a
		SL	30.77 c	40.83 b	71.16 e	150.33 ab
		HT	46.54 b	74.30 ab	79.28 d	111.84 b
	Root Surface area (cm^2)	CK	7.29 b	13.67 b	17.96 c	40.19 b
		SF	7.86 b	14.09 b	46.33 a	75.03 a
		SH	14.23 a	32.50 a	34.81 ab	52.97 ab
		SM	7.40 b	27.65 ab	32.21 b	60.92 ab
		SL	9.27 ab	18.54 b	26.34 b	54.55 ab
		HT	10.44 ab	23.64 ab	25.63 b	42.34 b
	Root volume (cm^3)	CK	0.17 b	0.58 b	0.81 c	2.30 b
		SF	0.32 ab	0.51 b	3.48 a	12.23 a
		SH	0.34 a	2.15 a	1.76 b	5.72 b
		SM	0.20 ab	1.04 b	1.50 bc	6.30 b
		SL	0.28 ab	0.72 b	0.82 c	11.01 ab
		HT	0.34 a	0.97 b	1.15 bc	2.08 b
	Root average diameter (mm)	CK	0.60 b	0.79 a	0.90 ab	1.20 ab
		SF	0.79 a	0.86 a	0.94 ab	1.08 b
		SH	0.81 a	0.91 a	0.93 ab	1.30 a
		SM	0.80 a	0.89 a	0.92 ab	1.01 b
		SL	0.73 ab	0.88 a	1.01 a	1.12 b
		HT	0.61 b	0.85 a	0.85 b	1.07 b

Note: Small letter in the same column means significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reduction in conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization.

3.5. Agronomic Characteristics

The plant height, node number of main stem, and branch number of main stem of FT1 showed a gradually increasing trend with the advancement of the growth period (Table 6). Plant height was the highest under the SF treatment at the seedling and grain-filling stages and the highest under the SH treatment at the flowering and maturity stages. The number of main stem nodes under the SM, SH, and SF treatments were remarkably higher than those under the other three treatments at the seedling stage, and the SH treatment had the largest number of main stem nodes at the other stages. The number of main stem branches was the largest under the SF treatment at the flowering and maturity stages and the largest under the SH treatment at the filling stage. The results in 2020 and 2021were similar.

Table 6. Effect of rice straw combined with inorganic fertilizer on agronomic traits.

Year	Item	Treatment	Period			
			Seedling Stage	Anthesis Stage	Grain-Filling Stage	Mature Stage
2020	Plant height (cm)	CK	25.33 b	58.80 b	59.16 c	68.90 b
		SF	31.00 ab	66.57 ab	72.73 a	80.30 ab
		SH	34.00 a	70.50 a	74.90 a	87.30 a
		SM	27.00 b	67.37 ab	68.53 b	79.50 ab
		SL	27.00 b	60.83 ab	68.87 b	74.73 b
		HT	25.67 b	58.93 b	65.67 b	72.80 b
	Number of main stem nodes	CK	4.33 b	7.33 b	8.10 b	8.77 c
		SF	5.33 ab	8.33 ab	9.67 a	10.67 ab
		SH	5.67 a	8.67 a	9.93 a	11.33 a
		SM	5.00 ab	8.33 ab	9.33 a	10.67 ab
		SL	5.33 ab	8.00 ab	9.67 a	10.00 b
		HT	4.67 b	7.67 b	9.33 a	10.00 b
	Number of branches of main stem	CK	-	4.67 c	7.00 b	9.33 b
		SF	-	8.33 a	10.00 a	11.33 a
		SH	-	7.33 ab	10.00 a	11.67 a
		SM	-	7.00 b	9.33 a	11.33 a
		SL	-	6.67 b	9.00 a	10.33 ab
		HT	-	6.00 b	8.33 a	9.33 b
2021	Plant height (cm)	CK	19.67 b	49.93 c	60.23 b	71.77 b
		SF	33.13 a	57.97 b	82.77 a	75.80 b
		SH	32.33 ab	70.67 a	75.73 ab	87.80 a
		SM	23.67 b	58.27 b	66.07 b	77.83 ab
		SL	26.00 ab	55.10 bc	68.37 b	83.70 ab
		HT	26.67 ab	58.00 b	69.00 b	72.23 b
	Number of main stem nodes	CK	4.33 b	8.00 bc	8.00 b	10.67 ab
		SF	5.67 a	8.00 bc	9.12 ab	9.53 b
		SH	6.00 a	10.00 a	11.33 a	12.33 a
		SM	4.00 b	8.67 b	9.10 ab	9.67 b
		SL	5.33 ab	8.67 b	10.00 ab	10.67 ab
		HT	6.00 a	7.00 c	9.33 ab	10.33 ab
	Number of branches of main stem	CK	-	5.00 b	8.33 b	10.00 b
		SF	-	7.00 a	9.00 ab	12.67 a
		SH	-	6.33 ab	10.00 a	12.33 ab
		SM	-	5.67 ab	9.67 ab	11.67 ab
		SL	-	4.00 b	8.67 ab	9.33 b
		HT	-	4.00 b	8.00 b	10.33 b

Note: Small letter in the same column means significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reduction in conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization.

3.6. Yield

The grain number per plant, grain weight per plant, and 100-grain weight of FT1 were the largest under the SH treatment and the smallest under the CK treatment (Table 7). Compared with CK, the SH treatment increased the FT1 yield by 142.05%. The SF, SM, SL, and HT treatments increased the yield by 120.22%, 50.59%, 39.82%, and 11.19%, respectively. According to the weather data (Table 1), it could be seen that the mean rainfall and temperature in 2021 were higher than those in 2020, which was conducive to straw decomposition. In addition, September was the key period for the flowering and grain filling of common buckwheat, and the mean sunshine hours in September 2021 were significantly longer than those in 2020, which was more conducive to assimilates accumulation and transport to grain, resulting in a higher yield in 2021 than in 2020.The effect of the year on grain number per plant, grain weight per plant, 100-grain weight, and yield of common buckwheat was not significant.

Table 7. Effect of rice straw combined with inorganic fertilizer on the yield of common buckwheat.

Year	Treatment	Grain Number per Plant (grain)	Grain Weight per Plant (g)	100-Grainweight (g)	Yield (kg hm^{-2})
2020	CK	51.67 d	3.04 c	3.15 e	671.80 d
	SF	106.67 b	5.75 b	4.62 b	2125.24 a
	SH	164.33 a	8.34 a	4.94 a	2202.28 a
	SM	91.67 bc	4.38 bc	4.04 c	1115.27 b
	SL	97.33 bc	5.19 bc	3.58 d	1200.26 b
	HT	72.67 c	3.52 c	3.58 d	863.22 c
2021	CK	61.00 c	3.01 c	2.68 f	960.3 f
	SF	98.33 ab	3.90 bc	4.68 b	2114.8 b
	SH	123.67 a	5.49 a	5.07 a	2324.4 a
	SM	83.67 b	4.90 b	3.56 d	1446.1 c
	SL	82.33 b	3.85 bc	3.40 e	1342.7 d
	HT	106.67 ab	4.15 bc	3.94 c	1067.8 e
Variance analysis	Year (Y)	NS	NS	NS	NS
	Treatment (T)	NS	8.458 **	85.809 **	978.631 **
	Y × T	NS	NS	6.281 **	23.981 **

Note: Small letter in the same column means significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reduction in conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization. ** represent significance at $p < 0.01$, and NS denotes non-significance at $p < 0.05$.

3.7. Fertilizer Use Efficiency

Compared with the CK and HT treatments, the fertilizer contribution rate of the SH treatment was the highest, followed by that of the SF treatment, and that of the SL treatment was the lowest (Table 8). The difference between treatments reached a statistically significant level. The fertilizer agronomic utilization rate of SL was the highest, followed by the SH treatment, and the difference among the treatments reached a significant level. The fertilizer agronomic utilization rate of the SH treatment was significantly higher than those of the other treatments. The results in 2020 and 2021were similar.

Table 8. Effect of rice straw combined with inorganic fertilizer on fertilizer utilization.

Year		Treatment	Fertilizer Contribution Rate (%)	Fertilizer Agronomic Utilization Rate (kg kg^{-1})
2020	Compared with CK treatment	SF	69.50 a	5.39 c
		SH	68.39 a	6.01 b
		SM	39.76 c	2.60 d
		SL	44.03 b	9.30 a
	Compared with HT treatment	SF	60.80 a	4.72 b
		SH	59.38 a	5.54 a
		SM	22.60 c	1.48 c
		SL	28.08 b	5.93 a
2021	Compared with CK treatment	SF	57.01 b	3.78 c
		SH	60.88 a	5.54 b
		SM	37.12 c	2.80 d
		SL	32.28 d	6.79 a
	Compared with HT treatment	SF	49.51 b	3.28 c
		SH	54.06 a	4.92 a
		SM	26.16 c	1.98 d
		SL	20.48 d	4.31 b

Note: Small letter in the same column means significant difference at $p < 0.05$. CK: no fertilization; SF: no straw with normal fertilizer; SH: full straw with 20% reduction in conventional fertilization; SM: full straw with 40% reduction in conventional fertilization; SL: full straw with 80% reduction in conventional fertilization; HT: full straw with no fertilization.

4. Discussion

4.1. Effects of Rice Straw Combined with Inorganic Fertilizer on Grain-Filling Characteristics and Starch Synthesis of Common Buckwheat

Grain filling is an important physiological process for the transport of photosynthetic products to grains and is a key process that determines grain weight and yield [24,25]. Richards' equation was used to simulate the grain-filling process of the superior and inferior grains of common buckwheat under rice straw combined with inorganic fertilizer. The R^2 of the curve equation of each treatment ranged from 0.939 to 0.991, which indicates that using Richards' equation to fit the grain-filling process of the superior and inferior grains of common buckwheat under the six treatmentsis feasible. The shape parameter N of the superior and inferior grains of common buckwheat under each treatment was less than 1, which indicates that FT1 is a synchronous grain-filling type [24].The difference ingrain filling betweenthesuperior and inferior grains after anthesis is manifested in two aspects, namely, R_0 and grain-filling rate [26]. The results showed that the R_0, G_{mean}, and G_{max} of the superior grains were all higher than those of the inferior grains.The resultsindicated that the superior grains start grain fillingearlier, have a faster grain-filling rate, obtain photosynthetic products preferentially, reach the maximum grain-filling rate in a shorter time, and reach fullness in a shorter time than inferior grains. This result is consistent with the results of Zhang et al. [26] and Zhang et al. [25]. The results of the experiment showed that the R_0, G_{mean}, and G_{max} of the superior and inferior grains of common buckwheat are larger in the SH and SF treatments than in the other treatments. This outcome may be due to the fact that the SH and SF treatments have sufficient nutrients to supply the growth of buckwheat at the early stage of growth, which increases the accumulation of grain-filling assimilates at the early stage of grain filling, promotes the early start of grain filling, and obtain more photosynthetic material [27].

The process of grain filling is the process of starch accumulation. The synthesis and accumulation of starch involve many enzymes, including SSS andSBE. These key enzymes play an important role in regulating starch synthesis and accumulation in thegrain [28]. Compared with CK, the SF and SH treatments could remarkably improve the SSS and SBE activities in superior and inferior grains, which may be due to the fact that conventional fertilization and the reduction ofa small amount of inorganic fertilizer are conducive to the accumulation of pre-anthesis assimilates, improve the amylase activity in grains, accelerate the starch synthesis and accumulation, and ultimately improve the grain yield [29]. Xu et al. [30] found that the activities of the SSS and SBE enzymes were lower in inferior grains with small grain weight. The results of the present study showedthat the superior grains (15 days after anthesis) reached the peak earlier than the inferior grains (20 days after anthesis) and had a higher peak value. These findings are consistent with previous research results [31], which indicated that low SSS and SBE activities may be one of the reasons for the poor filling of inferior grains.

4.2. Effects of Rice Straw Combined with Inorganic Fertilizer on Rhizosphere-Available Nutrient and pH

Rice straw is rich in carbon and potassium. After the rice straw is applied to the field, the nutrients in the straw are effectively released, which plays an important role in soil fertilization [32]. The present study showed that compared with CK (no straw with no fertilization), straw combined with inorganic fertilizer treatment could increase the nutrient, organic matter, and water contents of the rhizosphere. The main reason may be that the crushed straw is mulched on the soil surface, resulting in a remarkableincrease in soil organic matter content, increasing soil water-retention capacity, and improving soil water content [33]. Compared with inorganic fertilizers, the decomposition rates of nitrogen, phosphorus, and potassium in rice straw are slower, as decomposition is a long-term and continuous process. This process is beneficial to the accumulation of soil nutrient sink and thereforeincreases the nitrogen, phosphorus, and potassium contents in soil at thematurity of common buckwheat [34,35]. In the present study, each treatment had no remarkable effect on soil pH. This result is consistent with the results of Wang et al. [33], which suggests that the lack of effect may be due to the short period of straw returned to the field. It may also be due to the fact that although straw produced a large amount of acid substances in the decomposition process, it would soon recover because of the acid–base buffer capacity of the soil and would not affect the soil pH in the short term [36]. The present study showed that the contents of available K and available P in the SM treatment were considerably higher than those in other treatments. The main reason may be that the application of straw enhances the activity of soil microorganisms, increases the activity of phosphorus, and reduces the adsorption and fixation capacity of soil phosphorus [37]; therefore, the available phosphorus of the SM treatment was higher than that of the SF treatment. Under the condition of reducing the application of chemical fertilizers, straws will compete with crops for nutrients during the decomposition process, resulting in an insufficient nutrient supply. Moreover, compared with the SH treatment, the more chemical fertilizer application is reduced (SM treatment), the more intense the competition for nutrients between straws and crops; in turn, the release of crop root exudates is accelerated during the process of straw decomposition, thereby increasing the content of dissolved organic phosphorus. In addition, organic functional groups and organic acids released from root exudates can chelate with phosphorus to further accelerate the dissolution of phosphorus [38], thereby increasing the content of available phosphorus.

4.3. Effects of Rice Straw Combined with Inorganic Fertilizer on Yield

Zhao et al. [36] found that rice straw to the field and reducing the amount of inorganic fertilizer by 20% could maintain the yield of wheat at the same level, avoid the potential environmental risks caused by excessive fertilization, and reduce cost input. Wu et al. [32] found that under the rice–wheat rotation system, full rice straw and the reduction of nitrogen, phosphorus, and potassium by 15% can ensure the stable yield of wheat during the wheat season and reduce the risk of environmental pollution; therefore, this treatment has agronomic and economical benefits. Huang et al. [39] found that the combination of full straw mulching with 20–30% reduction in inorganic fertilizer could improve rice yield. The results of the present experiment showed that the yield of the HT treatment was lower than that of CK, which may be because the carbon-to-nitrogen ratio of rice straw is usually greater than 25, and the inorganic nitrogen in the soil will be assimilated by the microorganisms in the early stage of strawapplication. In turn, the content of available nitrogen is reduced, resulting in the poor growth and development of crop seedlingsand a reduction in the final yield [32]. In comparison, straw combined with inorganic fertilizer can improve the number of grains per plant, grain weight per plant, 100-grain weight, and yield of common buckwheat, and the SH treatment had the highest values. This outcome may be due to the reasonable application of inorganic fertilizer with straw, which will increase the content of inorganic nitrogen in soil, ensure the normal growth of seedlings in the early stage, and lay the foundation for the accumulation of grouting materials in the later stage. In addition, it may be related to the improvement of soil nitrogen-supply capacity in the later stage, which is more conducive to creating conditions for the growth and development of common buckwheat, promoting the growth of common buckwheat plants, and increasing the yield.

5. Conclusions

SH and SF could improve the fertility of the rhizosphere, increase the fertilizer contribution rate and fertilizer agronomy utilization rate, increase starch synthase activity in grains, promote thefilling of superior and inferior grains, and improve grain weight and final yield. Full rice straw combined with a 20% reduction in inorganic fertilizer should be considered when planting common buckwheat in Guizhou. Nutrient accumulation in the soil can be reduced as much as possible while meeting the nutrient demand for common buckwheat growth to ensure the stable or high yield of common buckwheat and reduce the environmental risk caused by unreasonable fertilization. However, the period of rice straw in the field in this experiment is short. Subsequent multiyear positioning experiments need to be carried out to further analyze the mechanism of rice straw combined with inorganic fertilizer on the grain filling and yield formation of common buckwheat and provide a theoretical basis for the development of the common buckwheat industry in Guizhou.

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