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Evaluating Rice Varieties for Suitability in a Rice–Fish Co-Culture System Based on Lodging Resistance and Grain Yield

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Abstract: Rice–fish co-cultures have been practiced for over 2000 years, and they have tremendous potential in terms of increasing food security and economic benefits. However, little research has been conducted into achieving stable yields and high lodging resistance with regard to rice while simultaneously promoting the harmonious and healthy growth of fish in rice–fish co-culture paddy fields. We conducted a field study aimed at selecting suitable rice varieties for rice–fish co-culture systems (encompassing both ratoon and main crop). This selection process was grounded in an evaluation of lodging resistance and grain yield among 33 rice varieties used throughout the studied region. The results revealed a range of lodging indices of the main crop for the second internode, spanning from 62.43 to 138.75, and the annual grain yield (main crop and ratoon crop) ranged from 7.17 to 13.10 t ha^{-1} within rice–fish co-culture systems. We found that the use of rice–fish co-culture farming could improve the milling quality, nutrient quality, and appearance quality of rice, though the improvement gained through co-culturing varied across rice varieties. Moreover, the lodging index of the three basal internodes of rice plants was significantly and positively correlated with the plant height and the culm fresh weight, but it was negatively correlated with the bending strength of the rice basal internodes. Additionally, the 33 tested rice varieties were clustered in accordance with their lodging resistance (i.e., high resistance with lodging indices 62.43–75.42; medium resistance with lodging indices 80.57–104.62; and low resistance with lodging indices 113.02–138.75) according to the hierarchical cluster analysis. The 33 rice varieties were also clustered in accordance with the annual (main crop and ratoon crop) grain yield (i.e., high yield with 11.17–13.10 t ha^{-1}; medium yield with 10.15–10.83 t ha^{-1}; and low yield with 7.16–9.88 t ha^{-1}). In all, 11 rice varieties were identified by a comprehensive evaluation as suitable varieties for grain production in the rice–fish co-culture system. These varieties displayed favorable traits, including a high annual rice yield, strong lodging resistance, and good grain quality. This is the first study to systematically evaluate rice varieties based on grain yield, lodging resistance, and grain quality in rice–fish co-culture systems.

Keywords: rice–fish co-culture system; rice varieties; lodging resistance; grain yield; paddy field screening

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1. Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the world's population, accounting for 21% of the global calorie intake and using 22% of the world's cereal land [1,2]. Given the current food crisis, it is very important to increase rice grain production to ensure food security [3,4]. Unfortunately, farmers have primarily relied on excessive

fertilization and pesticide use to increase rice yield, disregarding the detrimental effects on the environment [5–7]. A multispecies integrated farming system in rice paddy fields is an environmentally friendly model; it not only ensures food security and improves economic benefits, but it also protects the ecological environment of the farmland [8,9]. For instance, the rice–fish co-culture system is recognized as a sustainable form of agriculture as it utilizes the same land resources to yield both carbohydrates and animal protein, either concurrently or alternatively with rice [10].

Rice–fish co-cultures have been practiced for nearly 1200 years in South China, and they are considered to be a "globally important agricultural heritage system" (GIAHS) [11]. Rice–fish co-culture systems have tremendous potential for increasing the food security and economic benefits for farmers while simultaneously protecting paddy environments and resources [12–16]. Compared with conventional rice cropping, rice–fish co-culture systems reduce or eliminate pesticide and insecticide use since fish eat or uproot weeds and devour some insect pests for food [11]. Additionally, the presence of fish in paddy fields can facilitate the absorption, utilization, and transfer of nutrients for rice, thus reducing the need for artificial fertilization. This is achieved through the utilization of unconsumed fish feed and fish excretions, which serve as organic fertilizers [16].

Despite the increase in rice yield achieved by the rice–fish co-culture system compared with the rice monoculture system, few works have explored how various rice varieties will perform. Land managers must optimize and produce stable yields and high lodging resistance in rice, as well as promote the harmonious and healthy growth of fish in the paddy field. However, the interaction between these goals has yet to be explored. In rice–fish co-culture systems, the paddy is flooded until the rice is harvested, which is a necessary step to support fish and rice growth, though flooding also increases the risk of lodging and reduces the rice grain yield [17]. As a result, the practice may be less economically efficient in regions that frequently experience heavy rainfall, such as South China. Therefore, the screening of rice varieties with high lodging resistance and high yield becomes crucial for rice production in the rice–fish co-culture systems. Nevertheless, the screening of suitable rice varieties in rice–fish co-culture systems is primarily centered on a single aspect such as rice yield, grain quality, or lodging resistance of rice [18], and there are few evaluations that consider a combination of these essential factors. To address this gap, our study aims to comprehensively evaluate rice varieties in rice–fish co-culture systems for rice production, encompassing assessments concerning rice yield, lodging resistance, and grain quality.

China has a rich history of rice cultivation, and it possesses abundant resources in terms of rice varieties. In the late 1950s, Huang Yaoxiang, renowned as the father of semi-dwarf rice in China and affiliated with the Guangdong Academy of Agricultural Sciences, successfully tackled the challenge of lodging—a significant obstacle in terms of increasing rice production [19]. Huang accomplished this feat by crossbreeding Ai-zai-zhan 4 with Guang-chang 13, resulting in the world's first semi-dwarf indica rice variety, named Guang-chang-ai, which measures between 85 and 100 cm in height.

Since then, many semi-dwarf and high-yielding varieties have been bred, leading to an impressive increase in rice yield by approximately 20% to 30% [19–22]. Recently, growing demand for high-quality rice grains has driven the development of many new rice varieties with high yields, high quality, multi–resistance, and wide adaptability. However, not all rice varieties are suitable for all rice planting operations. For instance, the rice–fish co-culture system relies on the prolonged flooding of paddy fields to accommodate fish farming alongside rice cultivation. This system necessitates the use of rice varieties that exhibit both high lodging resistance and a high rice yield. Therefore, it is crucial to carefully select rice varieties from those that are widely planted and popularized to stabilize rice production and economics in the rice–fish co-culture systems.

In some cases, limited sunlight and insufficient accumulated temperatures mean that only one rice–growing season can be accommodated, such as Sichuan, Hubei, Fujian province, and some hilly areas in South China [23–26]. One possible solution to this issue is the production of ratoon rice, a regenerative practice referring to the cultivation of a second

rice crop utilizing the stubble remaining after the main crop is harvested. This method allows for a yield that is approximately 60% of the main crop while reducing the required resources and labor input by 50% [24]. Previous works have found that rice–fish co-culture farming could significantly increase the total grain yield of ratoon rice and improve the rice grain quality in the main and ratoon seasons [27]. Assuming a given rice variety could be harvested again in a ratoon season, with a commensurate reduction in cost inputs during the late rice-growing season and the ability for fish to thrive in the paddy fields for an extended period, the output/input ratio of the annual economic benefits in a single rice–fish co-culture system may surpass that of two traditional rice-growing seasons. Therefore, we conducted a comprehensive experiment in the paddy fields to screen rice varieties with a high yield and lodging resistance for rice–fish co-culture systems. We achieved this by planting and evaluating a total of 33 rice varieties that are widely promoted and extensively cultivated throughout the region.

2. Materials and Methods

2.1. Description of the Experimental Site

Field experiment was carried out in Baiyun experimental station (113°35′ E, 23°15′ N) of Guangdong Academy of Agricultural Sciences, Guangzhou, China. The field site has a subtropical monsoon climate characterized by warm winters and hot summers. The average temperatures of the main crop and ratoon crop of rice-growing period in 2021 were 26.2 °C and 29.4 °C, respectively. In 2021, the total amounts of precipitation were 826.7 and 454.4 mm, the total amounts of radiation were 169.7 and 214.9 $W \cdot m^{-2}$, and the total amounts of photosynthetically active radiation were 297.6 and 390.2 $\mu mol \cdot m^{-2}\ s^{-1}$ during the main crop and ratoon crop of rice-growing period, respectively (Figure 1). The soil is characterized as a sandy roam, and the main soil physicochemical properties include soil pH: 5.33, total organic matter: 17.97 g kg^{-1}, total nitrogen: 1.078 $g \cdot kg^{-1}$, total phosphorus: 0.284 $g \cdot kg^{-1}$, total potassium: 6.20 $g \cdot kg^{-1}$, total available nitrogen: 67.20 mg kg^{-1}, total available phosphorus: 8.09 mg kg^{-1}, and total available potassium: 23.00 mg kg^{-1}.

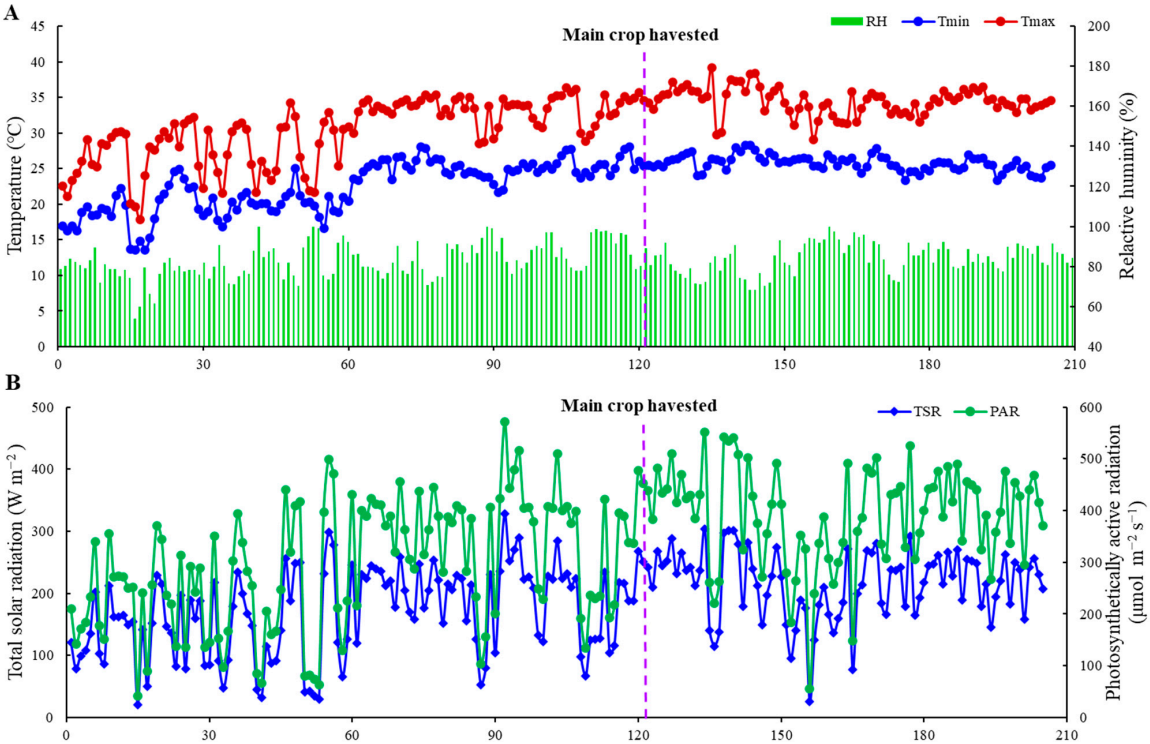


Figure 1. Daily max temperature (T_{max}), daily minimum temperature (T_{min}), daily relative humidity (RH), and rainfall (RF) (**A**), and daily total solar radiation (TSR), and daily photosynthetically active

radiation (PAR) (**B**) during main crop and ratoon crop of rice growth period in 2021 in Baiyun experimental station of Guangdong Academy of Agricultural Sciences, Guangzhou, China. The dotted line in the middle of the figure indicates the harvest time of the main crop.

2.2. Experimental Design and Agronomic Management

The treatment in this experiment consisted of two culture modes, i.e., ratooning rice–fish co-culture and ratooning rice monoculture. The subplot treatment was arranged by incorporating 33 indica rice varieties, including 25 inbred and 8 hybrid indica rice (*Oryza sativa* L.) varieties, which were randomly planted within the main plot. Each of the rice–fish co-culture areas (19 m × 8.2 m) consisted of two rice fields divided by a middle ditch with an "I" shape (0.5 m in depth and 0.6 m in width). All the rice varieties listed in Table 1 are cultivated extensively across South China. Before sowing, seeds were sterilized, and then they were soaked in water for 24 h at room temperature and germinated under suitable conditions. Geminated seeds were sown on March 8th. The seedlings of all rice varieties were then transplanted to the experimental plots on April 5th with 20 cm × 20 cm of space. Each rice variety was transplanted in 100 hills with 2–3 seedlings per hill. The rice grains were harvested on July 7th and September 28th for main crop and ratoon crop, respectively.

Table 1. The abbreviation of the 33 rice varieties in the experiment.

Abbreviation	Varieties	Abbreviation	Varieties	Abbreviation	Varieties
V1	Erguangxiangzhan 3	V12	Guguangyouzhan	V23	Wuyouyuehesimiao
V2	Huangguangyouzhan	V13	Yujingyouzhan	V24	Hengfengyou 387
V3	Huangsilizhan	V14	Hemeizhan	V25	Yexiangyou 9
V4	Huangguanghuazhan 1	V15	19 Xiang	V26	Yuenongsimiao
V5	Huangguangtaizhan	V16	Huahang 31	V27	Qingxiangyou 19 Xiang
V6	Wushansimiao	V17	Lvzhuzhan 1	V28	Qingxiangyou 033
V7	Yuehesimiao	V18	Lvnongxiangzhan 1	V29	Qingxiangyou 132
V8	Heguangsimiao	V19	Xinxingzimi	V30	Meixiangzhan 2
V9	Yuexiang 430	V20	Guang 8 You 2156	V31	Huanghuazhan
V10	Yuetaiyouzhan	V21	Guang 8 Youjinzhan	V32	Yuejingsimiao 2
V11	Nanjingzhan	V22	Guang 10 You 2156	V33	Xiangyaxiangzhan

In the ratooning rice–fish co-culture plot, 100 carps (*Cyprinus carpio* L.) were co-cultivated at a stocking density of 6500 per hectare with rice plants in the paddy field. Each carp fry, weighing 3–5 g, was introduced into the plot 10 days after rice transplantation and remained in the plot until the rice was harvested at the maturity stage of ratoon season. We used a carp cultivar, *Ruyuanshili 1*, which was the first fish variety bred by the Pearl River Fisheries Research Institute, Chinese Academy of Fishery Sciences, and it was specifically released officially for paddy fields in China.

A total of 150 kg N ha^{-1} in the form of urea was split into each plot for the main rice season: 60 kg N ha^{-1} as basal, 30 kg N ha^{-1} at mid-tillering, and 60 kg N ha^{-1} at the remaining leaf age of 2.5 [28]. Meanwhile, a total of 45 kg P_2O_5 ha^{-1} in form of superphosphate and a total of 120 kg K_2O ha^{-1} in the form of potassium chloride were applied one day before transplanting. In addition, all the treatment plots were maintained with a 10–15 cm water layer until the rice was harvested in rice–fish co-culture systems. In the rice monoculture system, the water layer was maintained at 2–5 cm during the first 10 days after transplanting to facilitate tillering, and then subsequent shallow wetting irrigation was conducted until 7 days before the rice was harvested. During the period of ratoon rice, the irrigation was referred to the management of Hu et al. (2023) [29]. All other paddy management was in accordance with standard cultural practices.

2.3. Measurement of Internode Morphological Traits

A total of 15 main culms were sampled from each variety of main crop to measure the plant height (distance between the plant base and the tip of the panicle), gravity center height (distance between the geometric center of gravity and the base of stem), panicle

length, and fresh weight of the three basal internodes (I_1, I_2, and I_3). The first internode was defined as the elongated basal internode (≥1.0 cm) near ground, and the other two internodes were labeled upwards sequentially. The length and fresh weight of the three basal internodes were all measured.

2.4. Measurement of Mechanical Parameters

Lodging-related morphological traits and lodging index were determined on the three basal internodes. The average breaking resistance of the three basal internodes (I_1, I_2, and I_3) from 33 varieties was determined using a portable lodging resistance detector (YYD-1, Tuopu instruments co., ltd, China) and following the methods laid out in Li et al. (2013) [30], respectively. The fixed distance between the two supporting points was 3 cm; the internodes were placed horizontally on the supporting points, and the force required for breaking the internode at the middle point was recorded. The minimum force of internode breaking was considered the breaking resistance (F). If the internode length was less than 3 cm, the breaking resistance was not measured, and the lodging index was not calculated. Mechanical parameters were then calculated according to the methods described by Niklas (1998) [31] and Islam et al. (2007) [32], so that the lodging index (LI) = bending moment (M)/breaking resistance (F). The bending moment (M) was considered equal to the distance from the basal of internode to tip of the panicle (cm) × the fresh weight of its corresponding section (g).

2.5. Determination of Grain Yield and Its Components

Grain yield and its components were measured according to the methods described by Peng et al. (2004) [33]. At the maturity stage, the rice plants were sampled from each rice variety, and the panicles were removed to measure the yield components. All grains were first separated from the rachis by manual threshing, and then they were divided into filled and unfilled categories using a winnower machine (CFY-II, 3.8 m^3 min, max air pressure: 1300 pa, Hangzhou, China). The total number of grains, filled and unfilled, and all the half-filled grains were counted and then averaged. The number of spikelets per panicle, the seed setting rate (100 × filled spikelets per hill of the total number of spikelets per hill), and the 1000 grain weight were also calculated for each sampled rice plant and then averaged. The total spikelet number was considered equal to the number of panicles per unit square area multiplied by the number of average spikelets per panicle. The grain yield was measured by harvesting 90 rice plants of each rice variety in each plot. In all cases, the grain moisture content was reduced to 14% by sun-drying before weighing.

2.6. Fish Yield and its Components

At the rice maturity stage, all the fish were harvested after draining water in the paddy field. To evaluate the influence of the rice variety on fish growth, all the fish were weighed separately, and the body length and width of each fish were measured using processing pictures that were taken while weighing each fish with ImageJ 1.53 k software (Wayne Rasband, National Institutes of Health, Bethesda, MD, USA), respectively.

$$\text{Weight gain rate (WGR, \%)} = 100 \times \frac{Average\ final\ weight - Average\ initial\ weight}{Average\ initial\ weight}$$

$$\text{Survival rate (\%)} = 100 \times \frac{Final\ number\ of\ fish}{Initial\ number\ of\ fish}$$

2.7. Grain Quality

Approximately 500 g of filled grains collected from the 33 rice varieties were dried in the sun until they reached a constant moisture and then analyzed for grain quality. An 80 g representative sample of grains was passed through a de-husker to obtain brown rice and was polished to obtain milled rice with a length $\geq 3/4$ that of its original length. Then, these brown and milled rice samples were weighed to calculate the percentages of brown rice, milled rice, and whole milled rice from the 80 g representative sample. Soluble protein content, amylose content, and gel consistency (GC) were measured using an Infratec-1241 grain analyzer (FOSS-TECATOR, Hillerød, Denmark). This instrument transmits near-infrared light through the grains. The grain samples were scanned within the range of 850–1050 nm, with a bandwidth of 7 nm. Each scan consisted of 100 data points. Grain length and width, chalky rice rate, and chalkiness degree of the 33 rice varieties were all measured using a Plant Mirror Image Analysis scanner (MICROTEK, Hsinchu, Taiwan, China). The images were processed with SC-E software v2.0 (Hangzhou Wanshen Detection Technology Co., Ltd., Hangzhou, China).

2.8. Data Analysis

Statistical analysis was performed in R version 4.1.0 (R Core Team 2021). Treatment differences were assessed using one-way ANOVAs, followed by Fisher's least significant difference post-hoc tests to identify significant ANOVA results. Bivariate trait relationships were summarized with Pearson correlations. The analysis was carried out using 'rcorr' function from the R package "Hmisc". To sort rice varieties by their grain yield and their relative lodging resistance, we performed hierarchical cluster analysis using the Euclidean distance between species as a proxy for similarity. First, we computed the Euclidean distance among the rice varieties with the 'dist' function in R. After we generated this information, we performed the hierarchical clustering with 3 levels using the 'hclust' function in R. All figures were constructed using R (R Core Team, Vienna, Austria) and SigmaPlot 14.0 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Comparison of Lodging Resistance of Different Rice Varieties

The plant height and the culm fresh weight of the 33 rice varieties were 90.95–112.99 cm and 14.07–23.31 g, and the averages of the plant height and the culm fresh weight of all rice varieties were 102.48 cm and 17.62 g, respectively (Tables 2 and 3). In most cases, the length of I_3 was longer than that of I_2, and I_{L2} was longer than I_{L1}. Similarly, the fresh weight of I_3 was heavier than I_2, and I_{FW2} was heavier than I_{FW1}. The ratio of I_{L123}/Height and I_{FW}/C_{FW} did not reach 50% of the whole culm and ranged from 8.83 to 27.4% and from 18.28 to 32.34%, respectively (Tables 2 and 3). Nevertheless, the bending strengths of I_1, I_2, and I_3 of most rice varieties were inversely correlated to the plant height and culm fresh weight (Table 4). In addition, the lodging index of the three basal internodes of the 33 rice varieties decreased from shoot to root (increasing internode number). Interestingly, only V1, V8, and V28 demonstrated an increase in the bending strength between the two freshest internodes (I_1 and I_2) (Table 4).

Table 2. The length of the three basal internodes of rice plant and the plant height of 33 rice varieties.

Varieties	Internode Length (cm)				Height (cm)	I_{L123}/Height %
	I_{L1}	I_{L2}	I_{L3}	I_{L123}		
V1	3.77 ± 0.14	7.45 ± 0.38	14.73 ± 0.41	25.95 ± 0.88	103.91 ± 0.90	24.96 ± 0.79
V2	3.61 ± 0.25	6.91 ± 0.34	12.77 ± 0.33	23.29 ± 0.78	102.89 ± 0.87	22.59 ± 0.62
V3	3.33 ± 0.26	5.56 ± 0.25	10.59 ± 0.34	19.47 ± 0.75	96.45 ± 1.50	20.16 ± 0.64
V4	3.92 ± 0.19	8.13 ± 0.53	14.49 ± 0.44	26.54 ± 1.08	104.87 ± 0.77	25.27 ± 0.94
V5	3.17 ± 0.17	5.74 ± 0.20	11.82 ± 0.39	20.73 ± 0.65	97.01 ± 0.91	21.36 ± 0.60
V6	3.67 ± 0.17	6.79 ± 0.35	14.63 ± 0.35	25.09 ± 0.82	96.11 ± 0.77	26.06 ± 0.73
V7	3.29 ± 0.17	4.79 ± 0.22	8.45 ± 0.31	16.53 ± 0.64	94.51 ± 0.94	17.47 ± 0.61
V8	2.85 ± 0.14	5.07 ± 0.24	9.82 ± 0.37	17.74 ± 0.63	94.69 ± 1.35	18.75 ± 0.66
V9	3.85 ± 0.22	7.46 ± 0.27	11.87 ± 0.58	23.18 ± 0.98	102.30 ± 1.22	22.66 ± 0.91
V10	4.20 ± 0.17	6.98 ± 0.44	13.50 ± 0.66	24.68 ± 1.18	100.28 ± 1.44	24.60 ± 1.12
V11	2.97 ± 0.11	5.11 ± 0.23	11.35 ± 0.53	19.42 ± 0.77	93.95 ± 0.84	20.69 ± 0.83
V12	3.68 ± 0.16	8.31 ± 0.41	12.89 ± 0.35	24.88 ± 0.75	104.51 ± 1.11	23.84 ± 0.77
V13	2.51 ± 0.13	4.03 ± 0.19	9.22 ± 0.60	15.76 ± 0.69	90.05 ± 1.59	17.50 ± 0.63
V14	4.39 ± 0.24	8.27 ± 0.39	13.79 ± 0.52	26.46 ± 0.97	106.72 ± 0.64	24.79 ± 0.88
V15	3.67 ± 0.21	8.33 ± 0.45	15.39 ± 0.38	27.39 ± 0.86	108.73 ± 1.51	25.15 ± 0.58
V16	3.76 ± 0.28	8.00 ± 0.44	13.02 ± 0.47	24.78 ± 0.94	103.87 ± 1.07	23.81 ± 0.77
V17	4.14 ± 0.22	8.48 ± 0.35	14.98 ± 0.32	27.60 ± 0.71	105.71 ± 0.79	26.12 ± 0.69
V18	4.08 ± 0.13	7.43 ± 0.25	14.31 ± 0.34	25.81 ± 0.60	107.91 ± 1.05	23.92 ± 0.52
V19	3.55 ± 0.11	6.80 ± 0.28	15.81 ± 0.34	26.16 ± 0.57	109.78 ± 1.17	23.83 ± 0.47
V20	3.89 ± 0.17	8.00 ± 0.44	13.02 ± 0.47	24.91 ± 0.73	104.28 ± 0.84	23.93 ± 0.78
V21	3.93 ± 0.22	8.27 ± 0.34	14.21 ± 0.28	26.41 ± 0.73	103.27 ± 0.81	25.56 ± 0.66
V22	3.29 ± 0.23	5.09 ± 0.35	11.72 ± 0.89	20.10 ± 1.25	105.66 ± 1.75	19.01 ± 1.10
V23	0.77 ± 0.11	3.11 ± 0.25	5.15 ± 0.17	9.03 ± 0.45	102.35 ± 1.25	8.83 ± 0.43
V24	4.27 ± 0.16	6.22 ± 0.27	13.75 ± 0.40	24.25 ± 0.74	106.65 ± 1.40	22.71 ± 0.56
V25	4.45 ± 0.19	7.82 ± 0.29	14.57 ± 0.24	26.83 ± 0.61	112.99 ± 1.42	23.75 ± 0.47
V26	4.07 ± 0.19	6.05 ± 0.29	12.23 ± 0.57	22.35 ± 0.96	99.13 ± 0.88	22.51 ± 0.89
V27	4.44 ± 0.13	7.03 ± 0.31	13.67 ± 0.34	25.14 ± 0.66	105.23 ± 1.08	23.89 ± 0.57
V28	3.71 ± 0.18	6.03 ± 0.47	12.10 ± 0.53	21.84 ± 1.00	111.21 ± 1.68	19.70 ± 0.98
V29	3.72 ± 0.18	4.93 ± 0.30	10.18 ± 0.42	18.83 ± 0.78	98.95 ± 1.61	19.02 ± 0.70
V30	3.70 ± 0.16	7.89 ± 0.49	14.46 ± 0.26	26.05 ± 0.81	101.75 ± 0.87	25.62 ± 0.80
V31	4.59 ± 0.14	7.61 ± 0.26	13.41 ± 0.42	25.61 ± 0.63	93.78 ± 0.95	27.40 ± 0.90
V32	4.07 ± 0.26	7.09 ± 0.47	13.43 ± 0.50	24.59 ± 1.15	105.88 ± 0.95	23.17 ± 0.99
V33	4.09 ± 0.25	8.17 ± 0.43	15.73 ± 0.48	27.99 ± 1.04	106.44 ± 1.09	26.41 ± 1.09

Note: In the table, I_{L1}, I_{L2}, and I_{L3} stand for the basal internode lengths 1, 2, and 3, respectively. IL_{123}/Height indicates the ratio of the three basal internode lengths to its stem height. Data are means ± SEs.

Table 3. The fresh weight of the three basal internodes of rice plant and the culm fresh weight of 33 rice varieties.

Varieties	Internode Fresh Weight (g)				Culm Fresh Weight (g)	I_{FW123}/C_{FW} %
	I_{FW1}	I_{FW2}	I_{FW3}	I_{FW123}		
V1	0.61 ± 0.03	1.64 ± 0.13	2.42 ± 0.08	4.68 ± 0.19	19.06 ± 0.65	24.69 ± 0.87
V2	0.73 ± 0.09	1.67 ± 0.13	2.44 ± 0.13	4.84 ± 0.30	18.71 ± 0.90	25.70 ± 0.71
V3	0.57 ± 0.05	1.33 ± 0.09	1.93 ± 0.07	3.83 ± 0.16	16.02 ± 0.73	24.22 ± 0.93
V4	1.34 ± 0.06	1.97 ± 0.09	2.49 ± 0.11	5.81 ± 0.21	18.49 ± 0.72	31.65 ± 0.95
V5	0.53 ± 0.03	1.28 ± 0.10	1.91 ± 0.09	3.72 ± 0.17	16.49 ± 0.66	22.58 ± 0.67
V6	0.98 ± 0.09	1.43 ± 0.08	2.39 ± 0.06	4.80 ± 0.20	16.59 ± 0.63	28.98 ± 0.59
V7	0.51 ± 0.04	1.06 ± 0.07	1.47 ± 0.08	3.05 ± 0.18	16.04 ± 0.59	18.92 ± 0.67
V8	0.65 ± 0.08	1.35 ± 0.06	2.05 ± 0.07	4.05 ± 0.16	19.07 ± 0.51	21.36 ± 0.87
V9	0.52 ± 0.04	1.37 ± 0.12	1.63 ± 0.09	3.51 ± 0.23	14.82 ± 0.99	24.19 ± 1.19
V10	0.62 ± 0.03	1.38 ± 0.11	2.08 ± 0.10	4.07 ± 0.21	15.76 ± 0.88	26.26 ± 1.08
V11	0.60 ± 0.05	1.24 ± 0.06	1.99 ± 0.11	3.82 ± 0.18	16.64 ± 0.87	23.32 ± 0.82
V12	0.68 ± 0.06	1.95 ± 0.06	2.21 ± 0.14	4.85 ± 0.20	19.16 ± 1.17	26.00 ± 1.04
V13	0.42 ± 0.03	1.02 ± 0.09	1.76 ± 0.11	3.19 ± 0.21	15.45 ± 0.76	20.52 ± 0.52

Table 3. *Cont.*

Varieties	Internode Fresh Weight (g)				Culm Fresh Weight (g)	I_{FW123}/C_{FW} %
	I_{FW1}	I_{FW2}	I_{FW3}	I_{FW123}		
V14	1.28 ± 0.09	1.82 ± 0.06	2.33 ± 0.06	5.43 ± 0.15	18.44 ± 0.49	29.58 ± 0.76
V15	0.64 ± 0.04	3.00 ± 1.15	2.30 ± 0.07	4.80 ± 0.22	17.15 ± 0.70	28.04 ± 0.60
V16	0.66 ± 0.06	1.71 ± 0.07	1.99 ± 0.10	4.36 ± 0.16	16.62 ± 0.68	26.51 ± 0.88
V17	0.99 ± 0.07	1.62 ± 0.07	2.10 ± 0.11	4.72 ± 0.21	14.67 ± 0.65	32.34 ± 0.80
V18	1.06 ± 0.05	1.35 ± 0.07	1.91 ± 0.10	4.32 ± 0.20	14.33 ± 0.54	30.09 ± 0.53
V19	1.00 ± 0.08	1.59 ± 0.12	2.76 ± 0.10	5.35 ± 0.22	18.22 ± 0.79	29.52 ± 0.70
V20	0.66 ± 0.06	1.71 ± 0.07	1.99 ± 0.10	4.36 ± 0.16	18.70 ± 0.73	23.65 ± 1.06
V21	1.24 ± 0.12	1.75 ± 0.10	2.24 ± 0.07	5.23 ± 0.22	16.27 ± 0.38	32.26 ± 1.29
V22	0.58 ± 0.05	1.28 ± 0.10	1.91 ± 0.09	3.77 ± 0.19	17.21 ± 0.67	22.33 ± 1.41
V23	0.56 ± 0.03	1.13 ± 0.09	1.99 ± 0.06	3.67 ± 0.16	20.10 ± 0.52	18.28 ± 0.66
V24	0.85 ± 0.04	1.87 ± 0.10	3.02 ± 0.12	5.73 ± 0.24	23.31 ± 0.91	24.63 ± 0.55
V25	0.92 ± 0.07	2.29 ± 0.13	3.19 ± 0.13	6.40 ± 0.30	22.30 ± 1.15	28.96 ± 0.66
V26	0.75 ± 0.03	1.50 ± 0.06	2.29 ± 0.09	4.54 ± 0.16	17.96 ± 0.62	25.47 ± 0.80
V27	0.77 ± 0.04	1.66 ± 0.07	2.32 ± 0.05	4.74 ± 0.10	18.83 ± 0.52	25.35 ± 0.58
V28	0.75 ± 0.06	1.76 ± 0.11	2.61 ± 0.09	5.12 ± 0.23	22.18 ± 1.01	23.38 ± 1.04
V29	0.61 ± 0.04	1.19 ± 0.11	2.02 ± 0.08	3.82 ± 0.21	18.82 ± 0.77	20.28 ± 0.66
V30	0.83 ± 0.07	1.38 ± 0.07	1.86 ± 0.06	4.07 ± 0.17	14.07 ± 0.53	28.98 ± 0.70
V31	1.23 ± 0.08	1.58 ± 0.10	1.95 ± 0.10	4.75 ± 0.25	15.56 ± 0.89	30.74 ± 0.74
V32	0.76 ± 0.05	2.01 ± 0.09	2.61 ± 0.09	5.38 ± 0.18	20.24 ± 0.61	26.75 ± 0.99
V33	0.82 ± 0.07	1.43 ± 0.07	2.03 ± 0.07	4.28 ± 0.14	14.09 ± 0.50	30.77 ± 1.19

Note: In the table, I_{FW1}, I_{FW2}, I_{FW3}, and I_{FW123} stand for the basal internode fresh weights 1, 2, and 3 and total fresh weight of basal internodes 1, 2, and 3, respectively. I_{FW123}/C_{FW} indicates the ratio of the fresh weight of the three basal internodes to the culm fresh weight. Data are means ± SEs.

Table 4. The internode breaking resistance and the lodging index of the three basal internodes of rice plant of 33 rice varieties.

Varieties	Internode Breaking Resistance (N)			Lodging Index		
	F_1	F_2	F_3	LI_1	LI_2	LI_3
V1	17.91 ± 0.98	16.50 ± 0.85	16.20 ± 0.49	112.88 ± 4.26	114.66 ± 4.98	96.63 ± 3.43
V2	21.81 ± 2.24	23.65 ± 1.91	26.79 ± 1.78	111.23 ± 12.56	82.60 ± 7.21	57.79 ± 2.08
V3	15.63 ± 0.91	19.18 ± 1.67	25.69 ± 1.27	110.42 ± 4.46	80.57 ± 6.25	49.87 ± 3.49
V4	18.72 ± 1.06	26.57 ± 1.73	26.46 ± 1.45	110.73 ± 7.48	71.30 ± 7.44	54.74 ± 3.30
V5	13.34 ± 0.75	13.28 ± 1.25	18.45 ± 1.07	126.18 ± 5.77	123.50 ± 9.51	72.61 ± 4.05
V6	13.98 ± 0.97	21.87 ± 3.24	20.84 ± 1.36	124.58 ± 9.36	80.94 ± 9.70	60.98 ± 3.72
V7	18.61 ± 1.15	16.94 ± 0.67	17.01 ± 0.63	89.62 ± 3.11	84.34 ± 2.82	74.02 ± 2.47
V8	17.14 ± 0.81	16.78 ± 0.85	28.67 ± 1.35	97.10 ± 6.86	104.62 ± 7.59	52.80 ± 2.22
V9	12.19 ± 1.04	20.63 ± 1.87	20.51 ± 1.63	139.16 ± 12.23	73.01 ± 5.93	58.91 ± 2.86
V10	18.87 ± 1.40	19.43 ± 0.96	17.06 ± 0.95	85.64 ± 3.07	75.26 ± 3.13	72.44 ± 2.97
V11	13.24 ± 0.67	17.34 ± 0.74	25.62 ± 1.76	123.03 ± 10.33	82.70 ± 3.83	51.98 ± 3.93
V12	21.47 ± 1.08	21.22 ± 0.87	21.61 ± 1.04	103.52 ± 7.40	89.34 ± 6.62	70.61 ± 3.66
V13	/	18.25 ± 0.97	18.23 ± 0.72	/	74.26 ± 4.30	65.33 ± 3.74
V14	14.92 ± 0.59	22.45 ± 1.51	22.74 ± 1.21	130.57 ± 5.18	85.20 ± 8.12	66.11 ± 4.19
V15	13.91 ± 1.01	25.78 ± 1.90	20.80 ± 1.23	149.38 ± 9.50	70.58 ± 3.41	69.84 ± 2.68
V16	15.07 ± 1.40	24.79 ± 1.99	23.63 ± 1.57	128.60 ± 12.11	69.57 ± 5.48	57.86 ± 3.45
V17	13.38 ± 0.92	24.11 ± 1.97	20.27 ± 1.35	116.93 ± 6.79	62.43 ± 5.83	57.19 ± 2.95
V18	14.77 ± 0.99	19.85 ± 1.69	18.63 ± 0.83	110.46 ± 6.90	75.07 ± 5.30	62.37 ± 2.14
V19	15.45 ± 1.27	16.73 ± 1.09	19.45 ± 1.73	142.61 ± 7.31	113.02 ± 5.27	87.47 ± 7.98
V20	17.18 ± 1.30	22.42 ± 1.33	23.08 ± 1.42	115.44 ± 5.89	83.70 ± 4.31	68.61 ± 4.90
V21	16.67 ± 1.01	24.13 ± 1.46	22.65 ± 1.19	106.96 ± 9.23	64.34 ± 3.20	55.57 ± 3.66
V22	18.26 ± 1.34	17.56 ± 1.04	18.29 ± 1.06	104.17 ± 6.99	101.21 ± 7.05	84.35 ± 4.87
V23	15.00 ± 0.53	14.80 ± 0.84	26.88 ± 0.90	145.56 ± 5.50	138.75 ± 10.5	65.12 ± 2.18
V24	18.57 ± 0.70	18.32 ± 0.81	17.81 ± 0.55	134.01 ± 2.83	126.21 ± 3.15	111.47 ± 3.83
V25	21.57 ± 1.40	34.22 ± 3.21	27.34 ± 1.93	128.10 ± 6.95	71.86 ± 3.53	72.25 ± 3.22

Table 4. *Cont.*

Varieties	Internode Breaking Resistance (N)			Lodging Index		
	F_1	F_2	F_3	LI_1	LI_2	LI_3
V26	18.56 ± 1.27	22.37 ± 1.20	27.31 ± 1.07	102.76 ± 9.27	75.42 ± 4.16	51.75 ± 2.01
V27	16.62 ± 0.77	18.18 ± 0.54	18.04 ± 0.48	121.98 ± 5.36	101.13 ± 3.79	85.81 ± 3.03
V28	27.07 ± 0.94	22.81 ± 0.90	21.25 ± 0.71	98.00 ± 4.17	102.37 ± 5.34	94.06 ± 3.76
V29	14.11 ± 0.76	17.90 ± 2.01	31.29 ± 1.76	138.42 ± 4.23	114.01 ± 12.2	50.73 ± 2.62
V30	19.61 ± 0.72	19.98 ± 1.22	16.84 ± 1.18	72.94 ± 2.45	66.61 ± 2.82	72.40 ± 11.68
V31	15.10 ± 1.09	21.78 ± 1.83	22.74 ± 1.78	102.68 ± 7.29	62.70 ± 4.71	47.69 ± 2.33
V32	19.54 ± 1.17	20.47 ± 0.84	20.26 ± 0.64	112.70 ± 4.60	98.72 ± 4.53	82.60 ± 3.60
V33	12.86 ± 0.90	14.31 ± 0.48	12.90 ± 0.34	121.34 ± 5.51	96.57 ± 5.25	86.77 ± 4.27

Note: In the table, F_1, F_2, and F_3 stand for the breaking resistance of basal internodes 1, 2, and 3, respectively; LI_1, LI_2, and LI_3 stand for the lodging index of basal internodes 1, 2, and 3, respectively. Data are means ± SEs.

3.2. Grain Yield and Its Components of Main Crop and Ratoon Crop among Different Rice Varieties

The grain yields of the 33 rice varieties of the main crop in the rice–fish co-culture system ranged from 4.59 to 9.04 t ha^{-1}. In comparison, the grain yields of the 33 rice varieties in the rice monoculture system ranged from 4.98 to 8.16 t ha^{-1} (Table 5). In rice–fish co-culture systems, the highest grain yield was V23 and the lowest was in variety V30. Interestingly, in the rice monoculture system, the highest yielding variety was V2 while the lowest yielding variety was still V30. The rice grain yield difference ($Y_{RF–RM}$) in 33 rice varieties between rice–fish co-culture and rice monoculture systems ranged from −36.87% to 24.89%. As the rice yield difference between the rice–fish co-culture and rice monoculture systems approached zero, the grain yield became more stable in both systems. The rice panicles, rice spikelets per panicle, seed setting rate, and 1000 grain weight of the 33 rice varieties were 195–345 m^{-2}, 95–205, 56.40%–89.70%, and 16.55–26.17 g in rice–fish co-culture systems, respectively. And those yield components in rice monoculture systems were 210–313 m^{-2}, 117–160, 67.29%–89.87%, and 18.60–25.02 g, respectively. Furthermore, the main crop yield had positive relationships with its rice panicles, spikelets per panicle, filled spikelets, seed setting rate, and 1000 grain weight in both rice–fish co-culture and rice monoculture systems. Meanwhile, the spikelets per panicle in the main season had a significantly positive correlation with filled spikelets and seed setting rate in both rice–fish co-culture and rice monoculture systems (Table 6).

The ratoon grain yield of the 33 rice varieties in the ratooning rice–fish co-culture system ranged from 1.97 to 5.30 t ha^{-1}, and in the monoculture system, it ranged from 2.16 to 4.62 t ha^{-1}. (Table 7). Specifically, in rice–fish co-culture system, V17 had the highest grain yield and V11 had the lowest grain yield. However, in the rice monoculture system, V24 was the variety with the greatest grain yield (4.62 t ha^{-1}), and V8 was the variety with the lowest grain yield (2.16 t ha^{-1}). In addition, the grain yield differences in the ratooning rice between the rice–fish co-culture system and monoculture system ranged from −28.62% to 70.42%.

Table 5. The grain yield and its components of the main crop of 33 rice varieties.

Varieties	Rice–Fish Co-Culture						Rice Monoculture						Yield Difference %
	Panicles (m^2)	Spikelets per Panicle	Toal Spikelets (10^2 m^{-2})	Seed Setting Rate %	1000 Grain Weight (g)	Yield (t ha^{-1})	Panicles (m^2)	Spikelets per Panicle	Toal Spikelets (10^2 m^{-2})	Seed Setting Rate %	1000 Grain Weight (g)	Yield (t ha^{-1})	
V1	300	191	572.88	89.70	19.79	6.40	240	154	369.60	89.87	20.98	7.17	−12.03
V2	245	139	340.28	81.15	22.74	7.37	272	149	405.28	85.07	23.29	8.16	−10.72
V3	195	156	304.64	82.80	21.70	6.83	270	154	415.80	82.61	22.02	6.82	0.15
V4	205	164	335.26	88.15	23.55	6.77	247	145	358.15	87.33	22.53	7.61	−12.41
V5	245	132	322.76	71.89	22.12	6.96	225	145	326.25	78.92	22.68	8.15	−17.10
V6	310	143	444.45	86.17	19.00	6.17	263	122	320.86	83.67	20.91	7.53	−22.04
V7	230	118	271.93	63.57	21.85	7.03	252	139	350.28	82.17	21.84	7.35	−4.55
V8	275	134	368.25	74.91	21.01	6.32	238	137	326.06	75.57	21.02	7.61	−20.41
V9	295	131	385.62	75.08	18.21	5.92	270	144	388.80	82.06	19.48	7.04	−18.92
V10	265	125	332.48	81.36	19.20	5.86	242	140	338.80	80.09	20.00	6.58	−12.29
V11	245	115	282.17	77.70	19.78	5.20	278	144	400.32	85.03	21.14	6.11	−17.50
V12	215	128	274.58	77.54	22.41	6.45	240	133	319.20	84.55	21.71	6.87	−6.51
V13	250	118	295.13	56.40	17.87	5.49	288	128	368.64	73.34	18.60	6.92	−26.05
V14	235	169	396.83	84.19	20.31	5.75	252	158	398.16	84.54	20.19	7.36	−28.00
V15	195	149	289.81	72.32	19.81	5.43	218	131	285.58	78.77	21.57	6.13	−12.89
V16	280	172	480.37	85.27	19.12	5.81	247	132	326.04	80.80	20.56	7.21	−24.10
V17	235	136	318.54	75.72	18.06	5.18	252	153	385.56	78.16	21.91	7.09	−36.87
V18	205	175	359.24	70.94	17.03	5.13	250	121	302.50	76.45	19.43	5.62	−9.55
V19	240	103	247.95	59.54	19.36	5.22	277	143	396.11	82.66	21.95	6.47	−23.95
V20	220	126	277.92	73.60	21.89	6.15	223	160	356.80	82.93	22.41	6.64	−7.97
V21	240	108	258.43	69.58	21.19	4.94	232	119	276.08	77.55	22.44	5.80	−17.41
V22	205	146	300.14	79.57	26.17	6.20	215	142	305.30	77.17	25.02	7.10	−14.52
V23	240	178	427.30	88.46	22.88	9.04	210	147	308.70	83.72	23.57	6.79	24.89
V24	275	177	487.18	78.60	25.43	8.01	288	138	397.44	73.13	24.28	7.91	1.25
V25	270	205	553.31	79.88	20.16	7.90	310	160	496.00	80.61	19.90	7.28	7.85
V26	260	153	398.58	87.62	21.81	6.93	313	131	410.03	84.27	21.57	6.74	2.74
V27	255	101	257.93	65.84	20.61	6.58	217	117	253.89	67.29	22.51	5.96	9.42
V28	270	134	362.71	63.62	20.95	5.41	273	126	343.98	73.24	20.83	6.13	−13.31
V29	/	/	/	61.51	20.28	6.51	258	131	337.98	76.51	21.33	6.55	−0.61
V30	215	198	425.22	74.59	16.55	4.59	268	140	375.20	82.98	20.10	4.98	−8.50
V31	345	124	428.47	69.09	18.90	5.80	258	149	384.42	83.15	21.03	6.42	−10.69
V32	235	113	264.96	65.13	19.11	6.09	240	158	379.20	85.64	21.99	6.18	−1.48
V33	250	95	238.57	66.57	18.84	5.77	297	129	383.13	82.63	20.32	6.16	−6.76

Table 6. The relationship between the rice grain yield and yield components of main crop and ratoon crop in rice–fish co-culture system.

Seasons	Indexes	Panicles	Spikelets per Panicle	Total Spikelets	Seed Setting Rate	1000 Grain Weight	Yield
Main crop	Rice–fish co-culture						
	Panicles	1					
	Spikelets per panicle	−0.05	1				
	Total spikelets	0.51 **	0.80 ***	1			
	Seed setting rate	0.10	0.68 ***	0.62 ***	1		
	1000 grain weight	−0.23	0.15	−0.04	0.30	1	
	Yield	0.14	0.27	0.26	0.37 *	0.69 ***	1
	Rice monoculture						
	Panicles	1					
	Spikelets per panicle	−0.04	1				
	Total spikelets	0.75 ***	0.58 ***	1			
	Seed setting rate	0.06	0.54 **	0.39 *	1		
	1000 grain weight	−0.41	0.19	−0.13	0.08	1	
	Yield	0.03	0.36*	0.23	0.14	0.22	1
Ratoon crop	Rice–fish co-culture						
	Panicles	1					
	Spikelets per panicle	−0.51 **	1				
	Total spikelets	0.46 **	0.43 *	1			
	Seed setting rate	−0.29	0.18	−0.12	1		
	1000 grain weight	−0.34	−0.07	−0.45 **	0.04	1	
	Yield	0.18	0.15	0.47 **	−0.12	0.00	1
	Rice monoculture						
	Panicles	1					
	Spikelets per panicle	−0.38	1				
	Total spikelets	0.59 *	0.45	1			
	Seed setting rate	0.23	0.63 *	0.75 **	1		
	1000 grain weight	−0.46	−0.15	−0.54 *	0.02	1	
	Yield	−0.01	0.31	0.16	0.53	0.12	1

Note: *, **, and *** significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Table 7. The grain yield and its components of the ratoon crop rice of 33 rice varieties.

Varieties	Rice–Fish Co-Culture						Rice Monoculture						Yield Difference %
	Panicles (m^2)	Spikelets per Panicle	Toal Spikelets (10^2 m^{-2})	Seed Setting Rate %	1000 Grain Weight (g)	Yield (t ha^{-1})	Panicles (m^2)	Spikelets per Panicle	Toal Spikelets (10^2 m^{-2})	Seed Setting Rate %	1000 Grain Weight (g)	Yield (t ha^{-1})	
V1	235	94	221.37	78.29	20.79	2.62	222	82.75	183.15	93.04	21.33	3.59	−27.02
V2	175	126	221.00	86.31	23.04	3.80	/	/	/	/	/	4.54	−16.30
V3	150	142	213.31	78.19	21.48	2.27	178	/	/	/	/	2.58	−12.02
V4	235	104	244.75	75.02	23.71	5.29	252	/	/	/	/	4.28	23.60
V5	/	/	/	/	/	/	/	/	/	/	/	/	/
V6	240	95	227.16	80.71	21.47	4.46	233	/	/	/	/	3.08	44.81
V7	225	102	230.17	82.95	21.53	2.85	247	/	/	/	/	3.22	−11.49
V8	155	99	153.34	74.78	21.52	2.61	/	/	/	/	/	2.16	20.83
V9	195	103	200.46	79.98	19.75	3.12	/	/	/	/	/	3.14	−0.64
V10	295	67	196.84	80.01	18.85	3.71	293	84.83	249.81	94.16	19.05	2.90	27.93
V11	310	64	198.04	78.49	20.48	1.97	253	71.18	180.37	92.94	21.44	2.76	−28.62
V12	240	96	230.66	83.92	20.97	3.71	278	77.13	213.82	93.86	21.38	3.67	1.09
V13	215	95	204.70	83.70	18.85	2.95	248	101.23	249.41	94.29	19.47	3.18	−7.23
V14	235	107	250.98	86.61	19.76	3.82	265	/	/	/	/	2.83	34.98
V15	220	117	258.29	79.02	19.22	5.08	218	/	/	/	/	3.12	62.82
V16	220	103	227.42	88.56	20.39	3.35	197	/	/	/	/	3.76	−10.90
V17	220	114	251.88	69.70	18.79	5.30	260	/	/	/	/	3.11	70.42
V18	290	121	350.42	78.24	16.99	3.38	313	77.59	243.77	93.44	17.28	3.51	−3.70
V19	270	93	252.34	72.50	19.64	5.06	220	/	/	/	/	4.00	26.50
V20	265	81	213.69	82.90	22.69	4.30	270	74.28	200.75	94.05	23.31	3.55	21.13
V21	225	91	204.03	79.94	21.61	3.24	275	71.06	195.71	93.80	22.61	3.34	−2.99
V22	225	68	152.74	83.94	24.94	3.41	252	/	/	/	/	2.98	14.43
V23	315	78	244.26	69.45	21.43	2.87	262	61.86	161.02	89.32	22.65	3.12	−8.01
V24	280	83	231.31	65.96	26.17	4.88	233	/	/	/	/	4.62	5.63
V25	245	150	366.46	84.12	20.67	5.20	235	/	/	/	/	3.63	43.25
V26	195	84	163.63	85.32	21.95	3.29	212	/	/	/	/	2.42	35.95
V27	250	117	293.66	79.04	22.20	4.25	240	90.63	217.16	94.34	22.40	4.17	1.92
V28	250	85	213.30	72.91	21.47	5.07	340	77.8	264.50	95.03	21.49	3.58	41.62
V29	255	95	242.17	79.72	21.42	5.00	313	79.16	246.62	94.63	21.08	3.95	26.58
V30	335	90	302.79	87.58	18.43	3.90	337	67.18	225.57	93.09	17.52	2.87	35.89
V31	275	111	304.00	82.00	18.67	2.92	247	/	/	/	/	3.00	−2.67
V32	300	82	244.84	70.83	19.70	3.46	247	/	/	/	/	3.70	−6.49
V33	385	72	278.70	73.58	17.22	4.09	377	66.04	247.00	93.84	18.07	3.66	11.75

Note: '/' indicates that there were no data of those rice varieties in the table because the sample was lost during the storage of the rice grain sample, and it could not be measured accurately.

In all, the sum of the grain yield of the main crop and ratoon rice ranged from 7.17 to 13.10 t ha^{-1}. Among the 33 rice varieties, V25 has the highest grain yield, followed by V24, V4, V23, V29, V2, V27, V6, V15, V17, V28, V20, V19, V26, V12, V7, V33, V22, V10, V14, V32, V16, V3, V9, V1, V8, V31, V18, V30, V13, V21, and the lowest is V11 in rice–fish co-culture systems.

3.3. Grain Quality of Main Crop among Different Rice Varieties

Rice–fish co-culture farming could improve milling quality, nutrient quality, and the appearance quality of rice, though to varying degrees among the 33 rice varieties. Within the 33 rice varieties, V5 (95.91%) has the highest brown rice rate when grown in rice–fish co-culture systems, followed by V14, V13, V24, V6, V31, V16, V21, V17, V4, V20, V25, V32, V3, V27, V23, V7, V12, V22, V8, V29, V28, V26, V30, V1, V19, V11, V33, V18, and the lowest was V15 (60.67%) (Table 8). Similarly, V14 achieved the highest milled rice rate at 79.45%, while V6 had the highest whole milled rice rate at 62.39%. V15 recorded the lowest milled rice rate at 51.14%, and V29 had the lowest whole milled rice rate at 40.34% (Table 8). The protein content, grain amylose content, alkali, and gel consistency of the 33 rice varieties in rice–fish co-culture systems were similar to the rice grain quality of the GB/T 1354-2018 standard (RICE) [34]. Additionally, the grain chalky rice rate and the chalkiness degree in the rice–fish co-culture system were under the second level of rice grain quality of the GB/T 1354-2018 standard (RICE) [34]. Overall, given our experimental design, we attributed these improvements to the influence of co-cultured carp fish, which improved the milled rice rate, the whole milled rice rate, the protein content, the chalky rice rate, and the chalkiness degree of the main crop.

Table 8. The grain quality of the main crop of 33 rice varieties.

Varieties	Brown Rice Rate %	Milled Rice Rate %	Whole Milled Rice Rate %	Protein %	Amylose %	Alkali	Gel Consistency (mm)	Length/Width Ratio	Chalky Rice Rate %	Chalkiness Degree %
Rice–fish co-culture										
V1	80.70	69.01	55.17	7.9	17.2	6.3	104	3.35	4	0.44
V2	/	/	/	/	/	/	/	/	/	/
V3	82.02	74.02	53.13	7.8	17.1	6.3	99	3.06	6	0.73
V4	82.29	72.35	40.46	7.9	17	6.4	97	2.85	5	0.53
V5	95.91	69.75	41.89	8.2	16.1	6.2	101	3.14	32	13.44
V6	82.71	72.42	62.39	8.2	16.2	6.3	76	3.30	7	2.85
V7	81.84	72.01	56.84	8.3	16.4	6.3	113	3.80	3	1.17
V8	81.60	67.50	41.49	8.2	16.1	6.3	81	3.13	6	2.29
V9	/	/	/	/	/	/	/	/	/	/
V10	/	/	/	/	/	/	/	/	/	/
V11	80.12	72.13	53.44	8.3	16.0	6.4	97	3.25	13	13.81
V12	81.76	73.99	54.90	8.3	15.9	6.4	112	3.37	21	11.43
V13	83.00	75.10	43.56	8.8	16.3	6.7	109	3.22	53	11.75
V14	92.49	79.45	43.55	8.7	16.4	6.7	128	3.15	14	5.24
V15	60.67	51.14	44.77	8.6	16.5	6.5	114	4.30	15	7.86
V16	82.36	71.91	56.83	8.7	16.4	6.6	116	3.22	13	7.05
V17	82.33	73.59	59.27	8.6	17.1	6.4	112	3.44	19	12.37
V18	79.37	56.91	46.33	8.5	17.3	6.4	123	4.51	3	1.34
V19	80.28	76.10	60.70	9.8	14.2	6.3	134	3.33	93	47.51
V20	82.21	72.79	49.70	9.8	14.3	6.4	105	3.29	82	43.52
V21	82.34	75.12	61.09	9.8	14.4	6.5	98	3.56	14	10.56
V22	81.66	69.29	42.06	7.0	14.6	5.2	109	3.07	8	1.42
V23	81.87	71.78	43.77	6.9	14.5	5.3	127	2.71	21	3.66
V24	82.81	68.30	48.50	7.0	14.5	5.4	131	3.13	8	3.68
V25	82.14	73.80	54.81	8.3	16.2	6.5	119	3.10	4	1.40
V26	80.99	71.07	59.89	8.2	16.3	6.4	132	3.19	7	2.68
V27	81.93	75.12	59.13	8.2	16.4	6.3	109	3.56	2	0.30
V28	81.13	66.40	49.09	7.8	15.9	6.0	117	3.81	2	0.20
V29	81.19	73.42	40.34	7.8	16.0	6.0	121	3.55	19	13.49
V30	80.87	67.74	53.47	7.9	16.5	6.0	115	3.51	3	2.20
V31	82.67	72.98	61.57	9.0	15.3	6.2	118	3.48	12	11.86
V32	82.11	76.40	62.15	9.0	15.5	6.3	121	3.42	4	3.27
V33	79.58	62.81	55.85	9.0	15.7	6.3	127	4.06	13	8.25
Mean	81.77	70.81	51.87	8.35	15.94	6.24	112.17	3.39	16.87	8.21
Rice monoculture										
V1	81.13	70.12	53.50	7.1	17.6	6.2	109	3.26	4	0.42
V2	/	/	/	/	/	/	/	/	/	/
V3	82.44	70.61	47.40	7.0	17.5	6.3	79	3.08	9	1.23
V4	82.80	69.51	53.40	7.1	17.8	6.3	134	2.95	5	1.44

Table 8. *Cont.*

Varieties	Brown Rice Rate %	Milled Rice Rate %	Whole Milled Rice Rate %	Protein %	Amylose %	Alkali	Gel Consistency (mm)	Length/Width Ratio	Chalky Rice Rate %	Chalkiness Degree %
V5	82.66	68.91	42.37	7.1	17.5	6.3	121	2.99	2	0.55
V6	81.81	71.78	59.80	7.4	18.1	6.3	118	3.15	3	0.78
V7	82.43	72.11	59.36	7.4	17.9	6.5	125	3.12	2	0.56
V8	81.79	70.96	45.87	7.5	17.6	6.6	122	3.06	3	0.45
V9	81.19	71.27	46.33	7.1	17.9	6.3	128	3.17	3	0.65
V10	/	/	/	/	/	/	/	/	/	/
V11	81.24	69.82	52.59	7.1	18.2	6.2	121	3.19	4	0.52
V12	82.14	69.23	52.41	7.2	17.8	6.4	117	3.30	10	3.2
V13	82.99	71.14	43.81	7.2	18.9	6.5	106	3.06	4	0.41
V14	81.31	69.94	50.53	7.3	18.9	6.6	123	3.12	90	53.5
V15	81.23	64.43	52.74	7.2	19.2	6.3	108	4.24	5	1.08
V16	82.09	70.84	54.84	7.6	16.2	8.3	95	3.18	2	0.83
V17	82.49	69.65	51.54	7.8	17.3	6.5	112	3.34	10	3.11
V18	80.04	61.17	42.06	7.7	17.8	6.1	127	4.72	8	1.11
V19	81.01	67.15	45.97	7.0	16.7	5.6	108	3.24	58	21.91
V20	81.64	67.14	41.70	6.9	16.0	5.6	126	3.21	22	6.96
V21	82.97	68.57	53.06	6.8	15.9	5.7	138	3.49	7	1.48
V22	82.13	67.04	35.31	6.4	15.2	5.5	112	3.29	11	2.45
V23	81.16	68.99	41.00	6.4	15.4	5.5	127	2.70	4	0.54
V24	82.56	66.10	42.23	6.5	15.5	5.5	120	3.26	13	2.32
V25	82.87	69.54	51.84	7.5	18.0	6.4	117	3.21	6	1.87
V26	81.67	70.05	55.14	7.5	17.9	6.3	116	3.23	2	0.17
V27	81.63	64.87	39.87	7.6	17.9	6.4	113	3.69	2	0.44
V28	82.64	67.30	44.00	7.0	16.9	6.1	134	3.84	21	3.88
V29	81.29	67.24	44.07	7.0	16.9	6.0	116	3.41	13	3.86
V30	80.91	68.41	47.84	7.1	16.8	6.1	134	3.44	1	0.12
V31	82.13	70.48	50.20	7.7	17.9	6.5	121	3.43	1	0.11
V32	82.47	72.42	63.56	7.6	17.8	6.5	107	3.41	1	0.09
V33	80.30	61.76	54.77	7.7	17.6	6.5	83	4.27	5	0.89
Mean	81.84	68.66	49.00	7.21	17.37	6.25	116.68	3.36	10.68	3.77

3.4. Fish Yield and Its Components

After harvesting the rice, we proceeded to harvest all the fish in the rice–fish co-culture paddy field. At the rice tillering stage, we co-cultured a total of 100 fry (2.761 g for each) (Table 9). At the maturity stage of ratoon rice, we harvested a total of 31 fish, weighing 979.6 g in total. The weight gain rate of the harvested fish was 1041%. The length and width of the harvested fish were 12.22 cm and 3.73 cm, respectively. However, the length/width ratio of these fish was lower than that of the fry. Unfortunately, the fish survival rate was only 31.00%.

Table 9. Fish yield and its components in rice–fish co-culture system.

Items	Quantity	Total Weight (g)	Weight (g per Fish)	Length (cm)	Width (cm)	Length/Width
Before cultured	100	276.1	2.76	6.23	1.69	3.69
Fish harvested	31	976.6	31.50	12.22	3.73	3.31

3.5. Cluster Analysis for Grain Yield of Main Crop and Ratoon Crop and for Lodging Index of Main Crop

Our clustering analysis found that yields between 6.77 t ha^{-1} and 9.04 t ha^{-1} could be considered a high yield, yields between 5.75 t ha^{-1} and 6.58 t ha^{-1} could be considered a medium yield, and yields between 4.59 t ha^{-1} and 5.49 t ha^{-1} could be considered a low yield. For the ratoon crop rice, the corresponding yield ranges were 4.88–5.30 t ha^{-1} for a high yield, 3.71–4.46 t ha^{-1} for a medium yield, and 1.97–3.46 t ha^{-1} for a low yield (Figure 2A,B). The grain yield of the three grades of the total annual rice yield can be categorized as follows: high yield (11.17–13.10 t ha^{-1}, V25, V24, V4, V23, V29, and V2), medium yield (10.15–10.83 t ha^{-1}, V27, V6, V15, V28, V17, V20, V19, V26, and V12), and low yield (7.16–9.88 t ha^{-1}, V7, V33, V22, V14, V10, V32, V16, V3, V9, V1, V8, V31, V18, V30, V13, V21, and V11) (Figure 2C). The cluster analysis for the lodging index of the main crop is shown in Figure 2D. The lodging index could also be divided into high resistance to lodging (LI = 62.43–75.42, V17, V31, V21, V30, V16, V15, V4, V25, V9, V13, V18, V10,

and V26), medium resistance (LI = 80.57–104.62, V3, V6, V2, V11, V20, V7, V14, V12, V33, V32, V27, V22, V28, and V8), and low resistance (LI = 113.02–138.75, V19, V29, V1, V5, V24, and V23). In summary, considering the total annual rice yield of both main and ratoon crop rice and the lodging index of the main crop, the following rice varieties, namely V25, V4, V2, V27, V6, V15, V28, V17, V20, V26, and V12, are potential candidates that could be suitable for cultivation in a rice–fish co-culture ecosystem. These rice varieties have shown promising performance in terms of yield and lodging resistance, making them favorable choices for rice–fish co-culture systems (Figure 2C,D).

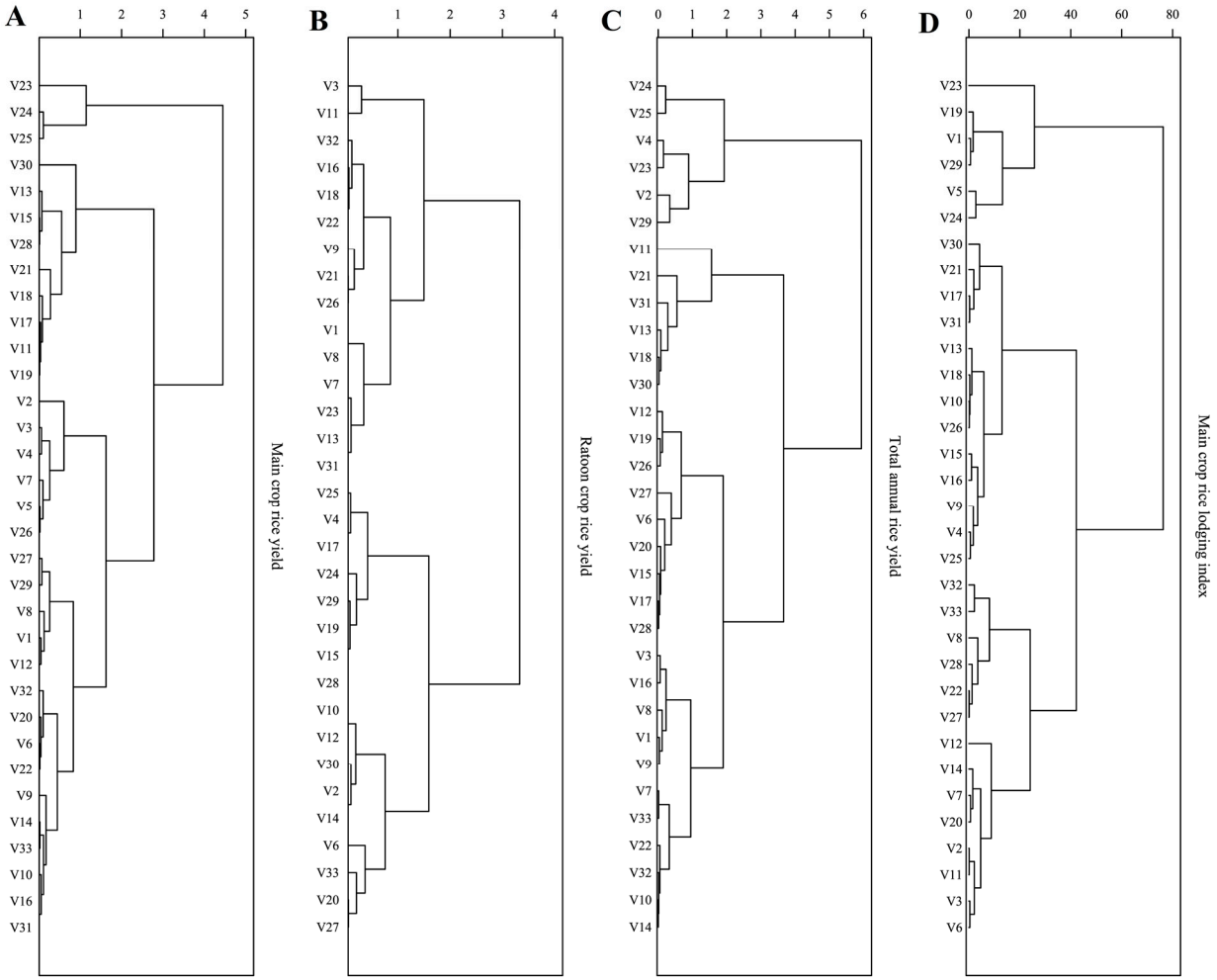


Figure 2. The hierarchical cluster analysis of the grain yield of main crop (**A**) and ratoon crop (**B**), the total annual rice yield (**C**), and the lodging index of main crop (**D**).

3.6. The Relationship between Lodging Index and Its Corresponding Morphological of Internodes of Rice Plant

The lodging index of the three basal internodes was significantly positively correlated with the rice plant height and the culm fresh weight (Figure 3). However, there was a significantly negative relationship between the lodging index, the internode length, and the bending strength of I_1, I_2, and I_3. In most cases, the rice plant height was positively correlated with the internode length, the internode fresh weight, the bending strength of I_1, I_2, and I_3, and the culm fresh weight. Additionally, a significant positive correlation was observed between the internode length and the fresh weight of I_1, I_2, and I_3. The internode length of I_1 and I_3 were significantly negatively correlated with the corresponding bending strength, while the fresh weight of the three basal internodes was significantly positively correlated with the bending strength of I_1 and I_3.

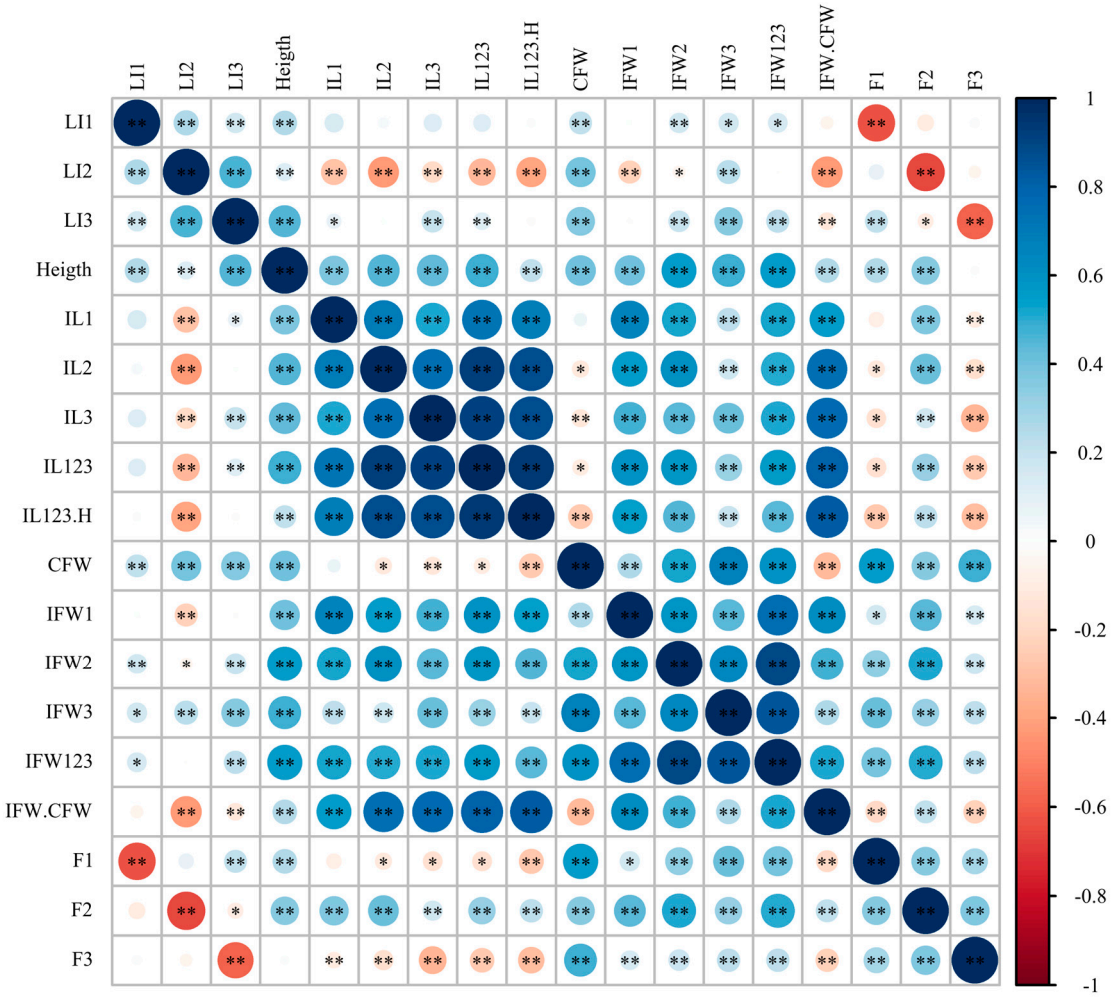


Figure 3. The relationship between internode lodging index and its corresponding morphological traits. * and ** in the figure indicated significant at $p < 0.05$ and $p < 0.01$, respectively. LI: lodging index; IL: internode length; IL123.H: the 3 basal internode length/height; CFW: culm fresh weight; IFW: internode fresh weight; IFW. CFW: the 3 basal internode fresh weight/culm fresh weight; F: internode breaking resistance; the numbers 1, 2, and 3 after the uppercase letter stand for the first, second, and third basal internodes of rice culm in the figure.

4. Discussion

Enhancing rice production and improving rice lodging resistance have been the key focus for sustainable development in rice–fish co-culture systems. In this study, we found that the lodging indices of most of the 33 rice varieties decreased with an increase in the internode length (Tables 3 and 4). Most varieties in the rice–fish co-culture system exhibited higher yields compared to the rice monoculture system. However, the yield difference between the two systems was not substantial, indicating that these rice varieties have relatively stable performance in the rice–fish co-culture systems relative to the rice monoculture systems (Table 5). These observations align with previous studies, and researchers have attributed the positive effects on rice production in the rice–fish co-culture systems to the activities of the fish. Fish actively feed on pests, which helps protect the rice plants from damage. Additionally, fish muddy the paddy water, a process by which they indirectly suppress weed growth, while their swimming and stirring of the water contribute to a healthier and stronger stem structure of the rice plants. These interactions between the fish and rice plants in the co-culture system provide multiple benefits that ultimately enhance the overall health and productivity of the rice crop [10,11,35]. In this study, according to the cluster analysis, V25, V4, V2, V27, V6, V15, V28, V17, V20, V26, and

V12 were screened by their higher total annual rice yield and lower lodging indices of the main crop (Figure 2), and the grain yield of these rice varieties was higher than the average of the rice yield in Guangdong Province (6.04 t ha^{-1}, Data from the National Bureau of Statistics of China).

At present, during the early and late rice-growing seasons, particularly at the maturity stage in the early season in South China, the weight of rice ears gradually increases, making them more susceptible to damage from typhoons and rainstorms. Therefore, it is crucial to select rice varieties with strong lodging resistance for cultivation in rice–fish co-culture systems. This measure ensures the stability and productivity of the rice crop, even in the face of adverse weather conditions. In this study, all the rice varieties screened for rice–fish co-culture systems had higher bending resistance of basal internodes of rice stems. Correspondingly, the length and the fresh weights of the first and the second internodes were 2.51–4.59 cm, 4.03–8.48 cm, 1.06–3.00 g, and 1.47–2.61 g, respectively (Table 2), while the corresponding values for high and medium lodging resistance indices of those rice varieties were 62.43–75.42 and 80.57–104.62, respectively (Table 4). In brief, shorter internodes and heavier fresh weight of the basal internodes lead to higher bending resistance and stronger lodging resistance, suggesting that the combination of a short internode distance and heavy internode fresh weights may promote tolerance of climatic disturbance and flooding [36–39]. Wang et al. (2021) [40] indicated that a shorter basal internode and a thicker stem wall could result in a lower lodging index. Gao et al. (2022) [17] also found that the bending moment and breaking strength were both increased for all the tested rice varieties under semi-water irrigation. Moreover, the rice yield may have more stability, while the lodging resistance of rice is stronger.

Among the various rice quality traits, it was observed that most rice varieties exhibited improvements in both the grains' milling quality and nutrient quality when co-cultured with carp in a paddy field. Additionally, the grain chalky rice rate and chalkiness degree in this system were lower compared to the grain quality standards outlined in GB/T 1354–2018, which was published by the State Administration for Market Regulation for rice. (Table 8). The characteristics of the grain quality were mainly affected by its genetics, and they were easily affected by the planting modes, environmental factors, and agricultural management as well, especially the appearance quality and the milling quality of rice grain [41–43]. In this study, the activities of fish, i.e., eating, swimming, stirring, etc., may increase the availability of nutrients in paddy soil and water, which would significantly improve the grain quality of rice in rice–fish co-culture systems [10]. This is consistent with other research, as Wan et al. (2019) [44] revealed that rice–fish co-culture farming reduced weed and pest pressures as well as rice grain chalkiness. Similarly, co-culture fish in paddy fields improved the grain protein content and soil nutrient availability. Recently, Wang et al. (2023) [45] found that a suitable stocking density of fish in paddy fields could significantly improve grain head rice rate and 2-acetyl-1-pyrrolone content in rice–fish co-culture systems. Likewise, Peng et al. (2022) [46] reported that the brown rice rate, milled rice rate, whole milled rice rate, and gel consistency in rice–fish co-culture systems were significantly higher than those in rice monoculture systems, and the chalky grain rate, chalkiness ratio, chalky amylose content, and the rice protein content decreased obviously in rice–fish co-culture systems. Moreover, the results of a meta-analysis indicated that co-culturing rice and aquatic animals (including fish, crab, frog, loach, duck, etc.) contributed to improvements in rice grain quality, and the positive effect held true regardless of the specific planting modes or environmental factors involved [16].

The yield of paddy fish is influenced by various factors, including temperature, dissolved oxygen, ammonia nitrogen, the nitrate nitrogen concentration of paddy water in the rice field, as well as the availability of food for the fish [14,47,48]. In our study, we observed that the average paddy fish gained 28.74 g between stocking and the final harvest (Table 9). However, we believe this poor growth is due to in-field challenges associated with fish loss, namely poor barrier construction. As such, this increase does not reflect genuine yields, which normally would be higher. In future endeavors, we will strengthen the construction

of field ridge facilities to reduce fish escapes from the paddy field. If anything, our results underscore the necessity of paying attention to the management of the paddy water and fry to stabilize the production of fish and the economic benefits of rice–fish co-culture systems.

In our current study, we identified several rice varieties among the 33 tested that exhibited higher rice yields than the average rice yield in Guangdong Province. These varieties include V23, V24, V25, V2, V7, V5, V26, V3, V4, V27, V29, V12, V1, V8, V22, V6, V20, and V32. Furthermore, we found that several rice varieties, namely V17, V31, V21, V30, V16, V15, V4, V25, V9, V13, V18, V10, V26, V3, V6, V2, V11, V20, V7, V14, V12, V33, V32, V27, V22, V28, and V8, exhibited low lodging resistance indices (less than 138.78). Additionally, the rice varieties V25, V24, V4, V23, V29, V2, V27, V6, V15, V28, V17, V20, V19, V26, and V12 achieved an annual grain yield of over 10.16 t ha^{-1} in rice–fish co-culture systems. Based on the findings from the Cluster and Spearman's rank correlation coefficient analysis, we have successfully identified and screened 11 rice varieties that are more suitable for cultivation in rice–fish co-culture systems in South China, i.e., V25, V4, V2, V27, V6, V15, V28, V17, V20, V26, and V12. All of these candidates demonstrate stable grain yield and strong lodging resistance.

5. Conclusions

In summary, suitable rice varieties should be screened in the system of rice–fish co-cultures because the rice grain yield of most rice varieties is different between rice–fish co-culture and monoculture systems. V25 (Yexiangyou 9), V4 (Huangguanghuazhan 1), V2 (Huangguangyouzhan), V27 (Qingxiangyou 19 Xiang), V6 (Wushansimiao), V15 (19 Xiang), V28 (Qingxiangyou 033), V17 (Lvzhuzhan 1), V20 (Guang 8 You 2156), V26 (Yuenongsimiao), and V12 (Guguangyouzhan) were screened based on the comprehensive evaluation of the 33 rice varieties such as annual rice production (main rice yield and ratoon rice yield), lodging resistance index, and rice grain quality in rice–fish co-culture systems. Those rice varieties had characteristics of high total annual rice yield, low lodging index, and good grain quality in rice–fish co-culture systems, and they might be more suitable for grain production in rice–fish co-culture systems. This is the first study to systematically evaluate rice varieties based on rice yield, lodging resistance, and grain quality in rice–fish co-culture systems, which would provide a scientific method for the selection of rice varieties in rice–fish co-culture systems.

Author Contributions: M.L.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—Original draft, Writing—Review and editing, Funding acquisition, Project administration. X.H.: Data curation, Formal analysis, Investigation, Methodology. R.H.: Investigation, Methodology. K.L.: Conceptualization, Writing—Review and editing, Funding acquisition, Project administration. X.Z.: Conceptualization, Writing—Review and editing, Funding acquisition, Project administration. J.P.: Investigation, Methodology. Y.F.: Investigation, Methodology. Y.L.: Writing—Review. X.W.: Investigation, Methodology. Q.Y.: Investigation, Methodology. Y.Y.: Investigation, Methodology. All authors have read and agreed to the published version of the manuscript.

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