A Novel Compost for Rice Cultivation Developed by Rice Industrial By-Products to Serve Circular Economy

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Abstract: Rice is the major staple crop worldwide, whereas fertilization practices include mainly the application of synthetic fertilizers. A novel compost was developed using 74% of rice industrial by-products (rice bran and husks) and tested in rice cultivation in Greece’s main rice producing area. Field experimentation was conducted in two consecutive growing seasons (2017 and 2018) and comprised six fertilization treatments, including four compost rates (C1: 80, C2: 160, C3: 320 kg ha⁻¹ of nitrogen all in split application, C4: 160 kg ha⁻¹ of nitrogen in single application), a conventional treatment, as well as an untreated control. A total of 21 morpho-physiological and quality traits were evaluated during the experimentation. The results indicated that rice plants in all compost treatments had greater height (8%–64%) and biomass (32%–113%) compared to the untreated control. In most cases, chlorophyll content index (CCI) and quantum yield (QY) were similar or higher in C3 compared to the conventional treatment. C2 and C3 exhibited similar or greater yields, 7.5–8.7 Mg ha⁻¹ in 2017 and 6.3–6.9 Mg ha⁻¹ in 2018, whereas the conventional treatment resulted in 7.3 Mg ha⁻¹ and 6.8 Mg ha⁻¹ in the two years, respectively. No differences were observed in most quality traits that affect the rice commodity. The current study reveals that in sustainable farming systems based on circular economy, such as organic ones, the application of the proposed compost at the rate of 6 Mg ha⁻¹ can be considered sufficient for the rice crop nutrient requirements.

Keywords: rice bran; husks; paddy rice residues; organic fertilizer; plant growth; renewable inputs

1. Introduction

Conventional agriculture plays the most significant role in meeting the food demands of the growing human population. However, the massive application of chemical fertilizers has disturbed field management, increasing the problem of soil, ground water, and air pollution at a global scale. Consequently, an increase in fertilizer application and a rise in the final food product prices has been observed, whereas the concerns of the farmers and the consumers are evident. Recent efforts have targeted toward the development of a healthier and nutrient rich food of high quality in sustainable compartments to ensure bio-safety. In agriculture, alternate means of soil fertilization relies on the organic inputs to boost nutrient supply and maintain the field management.

The use of composts and biofertilizers is within the scope of a sustainable agricultural system that provides an ecologically healthy and economically viable crop production, especially when they are derived by low-value by-products of the cultivated plants like rice (Oryza sativa L.).

Rice is a highly nutritious cereal that can be used as the source of several bioactive compounds. Specifically, brown rice is an excellent source of complex carbohydrates, vitamins, minerals, phytosterols,
and dietary fibers [1]. However, because of the global preference for consumption of milled rice, most nutritional parts of the grain are lost during the milling process by the removal of the pericarp, the seed shell, and the embryo of the grain, known as rice bran (RB), which contains rice bran oil and holds approximately 10% of the overall rice yield [2]. RB is rich in protein, vitamins, essential minerals, and antioxidant compounds [3]. Previous studies indicated the possible use of RB as a natural fertilizer containing 2.5% nitrogen, 3% phosphorus, 2.3% potassium, and 1% magnesium, whereas the C/N ratio is approximately 19 [4]. It is estimated that the world annual production of RB amounts to 76 million tons [5,6].

Another notable product derived from the de-husking process in rice mills is the seed shells, known as husks or hulls. These are parts of the rice seed (palea and lemma) and they represent 20%–22% of the milling process’s residuals [7]. Rice husks (RH) are composed of 28% cellulose, 28.6% hemicelluloses, 24.4% lignin, and 18.4% extractive matter [8]. According to Vadivel and Brindha [9], the global production of RH is very significant and falls in the range of 20 million tons annually. Therefore, the utilization of the RH is of high importance. Since RH are inedible by humans, but suitable for animal feed [10], they can be used in various non-food applications. The most important uses of RH are the production of energy (fuel) and ethanol, the pyrolysis for silicon dioxide production [7], the smoking of foods, and the acceleration of the bioremediation process into the soil [11]. Ogbo and Odo [12] confirmed the suitability of RH as a carrier for biofertilizer production. Moreover, Evans and Gachukia [13] reported that parboiled fresh husks can be used as a low cost perlite substitute in greenhouse substrates without any significant reduction in plant growth or quality, while at rates up to 40% (v/v) no significant reduction was observed impacting plant tissue N (without N depletion). Extracts from RH act not only against phytopathogenic fungi, such as root rot seedling rice [14], but also against algae [15] and bacteria [16]. Expanding the positive effects of RH on rice straw, Iranzo et al. [17] found that the characteristics (physical, chemical, microbiological properties) of the rice straw were complementary to those of the sewage sludge for their application as a compost.

Despite the fact that the activity of RB and RH were investigated intensively, especially the antioxidant activity of RB and the phytochemical of RH, their simultaneous exploitation in sustainable farming systems has not yet been deeply investigated.

The aim of the current study is to investigate the potential use of a natural fertilizer, produced by rice by-products such as a combination of RB and RH, in rice cultivation through the evaluation of agronomic and physiological parameters, as well as of rice productivity and quality indices, serving the principals of circular economy. Extending the research outcomes, this natural RB fertilizer can be utilized in organic rice cultivation.

2. Materials and Methods

2.1. Site and Climatic Conditions

Two field experiments were conducted in two consecutive years, 2017 and 2018, at the Experimental Station of Kalochori, Thessaloniki, Greece (40°36’58.75” N, 22°49’51.16” E). The soil consisted of 22% clay, 50% silt, 28% sand, with 2.84% organic matter, electrical conductivity 1.3 dS m^{-1} and pH 7.5. Temperature and relative humidity were constantly recorded throughout both cultivation periods, in order to compare the annual meteorological datasets. Table 1 presents the monthly averages of temperature and relative humidity during the two growing seasons of the experimentation, with the values being the norm of a typical Mediterranean climate.
2.2. Compost Preparation and Properties

Initially, the compost formula was developed in preliminary experiments during 2016, where the composting mixture was placed under a Poly Vinyl Chloride (PVC) PVC soil cover sheet and exposed to an aerobic digestion in heaps of approximately 1.5 × 1.5 × 0.5 m$^2$ volume Figure 1a. The materials were mixed at a weekly basis, whereas moisture was controlled at 40%–60% by watering with tap water every 5 days. The temperature was checked to be never above 60–65 °C at the center of the pile using a hand-held thermometer. A temperature of 60–65 °C was not surpassed, to avoid alterations that might take place in the microflora and losses of NH$_4^+$-N. The composting process was performed for at least 40 days, while the C/N ratio was being checked on a frequent basis.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>2017</td>
<td>June</td>
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<td>19</td>
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</tr>
<tr>
<td></td>
<td>October</td>
<td>11</td>
<td>26</td>
</tr>
</tbody>
</table>

2.2.3. Compost Preparation and Properties

Table 1. Monthly temperature and relative humidity during the rice growing seasons in 2017 and 2018 at the experimental site. Minimum, maximum, and average values of each year are reported, averaged over each month.

The raw materials during composting process (a) and the compost bin (b).

In 2017 and 2018, all raw materials were placed into a custom automatic composting bin of 1.5 Mg capacity designed and constructed by DEMETER’s team to optimize the process [Figure 1b]. The materials were mixed thoroughly every 5 days, the moisture was kept between 40%–60%, while the compost temperatures were ranging between 60–65 °C. The materials were left for at least 40 days to complete the composting process, when the C/N ratio reached a value lower than 12.

The raw materials used for the compost consisted of rice milling industry by-products at a level of 74% approximately. The compost consisted of: 160 kg RB (65.5%), 20 kg RH (8.2%), 40 kg organic chicken manure (CM) (16.4%), 24 kg zeolite (9.8%), and 0.333 kg of “Neudorff Radivit” commercial compost accelerator (0.1%), containing several species of Bacillus spp. and Aspergillus spp. to facilitate humification. In general, the majority of the species of the microorganisms in the compost accelerator belong to the genus Bacillus, which transform nitrite to nitrate, whereas the mold fungi, Aspergillus sp.,
transforms and mineralizes cellulose, lignin, and oily matter. In addition, after the second week of the composting process two different species at the larval stage were recorded in the composting materials: (i) the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae) and (ii) the domestic fly, *Musca domestica* (Diptera: Muscidae).

Laboratory analysis of the raw materials was carried out, while the samples were collected before mixing and during the composting process. The results are reported in Table 2. Specifically, total organic carbon (C), total nitrogen (N), available phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) were determined by the following standard analytical methods: total organic carbon content by the wet oxidation method [18], total nitrogen by macroKjeldahl method, available phosphorus by Olsen’s method [19], whereas potassium and selected macro- and micronutrients by atomic emission spectrometry with inductively coupled plasma (ICP-AES). The pH of the mature compost ranged between 6.3 and 7.8, whereas the electrical conductivity was 0.73 dS m⁻¹.

### Table 2. Laboratory analysis of the raw materials (RH, RB, CM, and zeolite), the initial composting mixture at 0 days, and the composting mixture at 20 and 40 days (mature compost), utilized in 2017 and 2018 experimentation.

<table>
<thead>
<tr>
<th>Material</th>
<th>TOC%</th>
<th>TN%</th>
<th>C/N Ratio</th>
<th>P %</th>
<th>K %</th>
<th>Ca %</th>
<th>Mg %</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH (raw material)</td>
<td>47.05</td>
<td>0.29</td>
<td>162.2</td>
<td>0.04</td>
<td>0.13</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>RB (raw material)</td>
<td>41.02</td>
<td>2.37</td>
<td>17.3</td>
<td>1.99</td>
<td>1.78</td>
<td>0.80</td>
<td>0.83</td>
</tr>
<tr>
<td>CM (raw material)</td>
<td>40.60</td>
<td>4.00</td>
<td>10.15</td>
<td>4.25</td>
<td>4.50</td>
<td>3.50</td>
<td>0.12</td>
</tr>
<tr>
<td>Zeolite (raw material)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.009</td>
<td>1.52</td>
<td>2.17</td>
<td>0.63</td>
</tr>
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<td>Composting mixture/0 days</td>
<td>44.05</td>
<td>2.26</td>
<td>19.5</td>
<td>2.20</td>
<td>2.31</td>
<td>3.08</td>
<td>0.93</td>
</tr>
<tr>
<td>Composting mixture/20 days</td>
<td>34.70</td>
<td>2.15</td>
<td>16.1</td>
<td>2.81</td>
<td>2.14</td>
<td>3.75</td>
<td>1.30</td>
</tr>
<tr>
<td>Composting mixture</td>
<td>25.30</td>
<td>2.65</td>
<td>9.5</td>
<td>2.65</td>
<td>2.00</td>
<td>2.60</td>
<td>1.12</td>
</tr>
</tbody>
</table>

TOC, total organic carbon; TN, total nitrogen; C/N ratio, carbon/nitrogen ratio; P, phosphorous; K, potassium; Ca, calcium; Mg, magnesium.

### 2.3. Experimental Setup

The size of each experimental plot area was 11 m² (5 × 2.5 m), whereas the experiment was arranged in a randomized complete block design (Figure 2), with five replications for each treatment and six fertilization treatments.

![Figure 2](image-url) Experiment setup (RGB image taken by drone). Differences between fertilization treatments in biomass and green color are visible from early stages.

The fertilization treatments were: compost application of (i) 80 kg ha⁻¹ N (C1) in split application, (ii) 160 kg ha⁻¹ N in split application (C2), (iii) 320 kg ha⁻¹ N (C3) in split application, (iv) 160 kg ha⁻¹ N in single application (C4), (v) an untreated control (CONTR) and (vi) 160 kg ha⁻¹ nitrogen chemical fertilizer (standard fertilization practice) (CONVEN). The C2 treatment had nitrogen units equivalent...
with that of the CONVEN, whereas the C4 treatment was included in the study to evaluate the efficiency of the compost as a slow release fertilizer. Beside C4, the fertilization scheme followed the local and international standard practices for rice cultivation, where the amount is divided in three increments: 40% of N units are incorporated as basal before flooding, 40% is applied at the tillering stage and similarly the rest 20% at the panicle initiation stage. Before flooding and sowing, the basic fertilization was achieved with the incorporation of compost treatments in each plot into the upper 5–10 cm of the soil, using a plot rotary tiller machine. At tillering and at panicle initiation stages, the compost treatments were achieved as surface fertilization.

The different types of soil treatments and their abbreviations are presented in Table 1. According to (i) the nitrogen concentration of mature compost presented in Table 2 and (ii) the amount of nitrogen units presented in Table 3, the relative amount of compost at C1, C2, C3, and C4 treatment is 3.0, 6.0, 12.0, and 6.0 Mg ha\(^{-1}\), respectively.

**Table 3.** Different fertilization treatments, their abbreviations, and the amount of nitrogen units (kg ha\(^{-1}\)) were used at different stages during the rice-growing season (before sowing, at tillering, and at panicle initiation).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Basic Fertilization (Before Sowing), kg ha(^{-1})</th>
<th>First Surface Fertilization (at Tillering), kg ha(^{-1})</th>
<th>Second Surface Fertilization (at Panicle Initiation), kg ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>32</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>C2</td>
<td>64</td>
<td>64</td>
<td>32</td>
</tr>
<tr>
<td>C3</td>
<td>128</td>
<td>128</td>
<td>64</td>
</tr>
<tr>
<td>C4</td>
<td>160</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CONTR</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CONVEN</td>
<td>64</td>
<td>64</td>
<td>32</td>
</tr>
</tbody>
</table>

Seeds (0.220 kg) of the Greek commercial variety DION (japonica type), which belongs to the European Core Collection, were directly seeded into each of the flooded plots on 9 June 2017 and on 6 June 2018, respectively. Besides fertilization, plots treated with compost were kept free from weeds by hand weeding, whereas standard cultural practices for rice cultivation were conducted including harrowing, tillage, and lazier leveling. The experiments were harvested when the plants reached the physiological maturity stage on 10 October 2017 and 9 October 2018, respectively.

2.4. Growth Parameters

During the experimentation period, the following traits were assessed at various stages: (1) Plant height (PH; cm) at 42, 60, and 80 days after the sowing (DAS), by measuring the main shoot from the ground level up to the tip of the largest leaf stretched of 30 random rice plants per plot; (2) total dry aboveground biomass (BT; Mg ha\(^{-1}\)) at 85 DAS and at maturity stage, by cutting three random samples from each plot at ground level, covering an area of 0.25 m\(^2\), and weighting it after drying for 48–72 h in an air oven at 70 °C until constant weight; (3) grain yield (Mg ha\(^{-1}\)) by cutting two samples of 1 m\(^2\) each per plot, the plants were cut at the ground level and they were harvested by using an electric panicle harvester.

2.5. Physiological Parameters

The chlorophyll content of the leaves was measured at 32, 42, 62, 90, and 105 DAS using a portable chlorophyll content meter (CCM-200, Opti-Sciences, Tyngsboro, MA, USA). For this purpose, ten measurements were acquired from different plants in each plot, from the second youngest leaf (counting from the plant apex) of the main shoot with the same orientation toward the sun.

At 32, 62, 90, and 105 DAS, the quantum yield (QY) of photochemical energy conversion at PSII was measured at midday, using a FluorPen FP100 (Photon Systems Instruments, Brno, Czech Republic) on light-adapted leaves. For this purpose, ten measurements were taken in each plot, from the upper
third of the second youngest leaf (counting from the plant apex) of the main shoot, with the same orientation toward the sun [20]. Based on the phenological growth/BBCH stages, the 32, 62, 90, and 105 DAS, in which CCI and QY were measured, corresponded to the tillering stage, booting stage, filling stage, and maturity stage, respectively.

The harvest index (HI) was also calculated as the ratio of grain yield to total dry aboveground biomass. HI is considered as a measure of biological success in partitioning assimilated photosynthate to the harvestable product [21].

2.6. Phenotypic and Quality Analysis

Brown rice was obtained using a dehusker machine (Taka Yama, TW Grandeur Machinery Co., Taichung, Taiwan), whereas white rice was obtained subsequently using a whitening machine (SATAKE type TM 05C, OLMIA).

Total milling yield (TMY) was determined as the percentage ratio of dehulled (brown) rice grains’ weight to the paddy rice weight, whereas the 100 grains weight (100GW) was determined using a precision electronic scale model KERN 573 (Kern & Sohn Gmbh, D-72336, Balingen, Germany). Whole milling yield (WMY), percentage of chalkiness (CH), as well as the grains’ dimensions paddy rice length (PL), width (PW), and length/width ratio (PR), the brown rice length (BL), width (BW), and length/width ratio (BR), the white rice length (WL), width (WW), and length/width ratio (WR) were determined by measuring the two samples of 100 grains for each plot, using the SeedCount SC4 digital imaging seed analyzer (SeedCount Australasia, Condell Park, Australia). Finally, amylose content (% AMY) was determined in all the samples as per the procedure of ISO 6647 [22].

2.7. Statistical Analysis

The statistical analysis (ANOVA) was carried out using the computer software MSTAT-C version 1.41 (Michigan State University, East Lansing, MI). All measures and derived data were objected to a combined over-year analysis of variance (Experiment Model Number 15, One Factor Randomized Complete Block Design Combined over Years), with compost treatment as the main factor. In cases where the factor year was significant, the data were objected to analysis of variance separately for each year (Experiment Model 7 Number, One Factor Randomized Complete Block Design). Fisher’s Protected LSD procedures were used to detect and separate mean treatments differences at $p < 0.05$. The combined analysis of data was justified following the Bartlett’s test for homogeneity of variances, which indicated that data were not heterogeneous.

3. Results and Discussion

The laboratory analysis results of the main raw material of compost (Table 2), i.e., the RB, agrees with those of Hossain et al. [4], who report that RB has about 2.51% nitrogen, 1.99% phosphorus, 1.78% potassium, and C/N ratio 19. The key element of the composting process is the production of a stable and mature end-product, suitable to be applied as fertilizer or soil amendment [23]. In our study, the C/N ratio was stabilized very soon (approximately in 40 days) at values below 12, revealing that the maturing of compost was achieved. This significant reduction of C/N ratio indicates a rather fast decomposition of the organic material added and subsequent nutrient release, which is arguably attributed to the enhancement of raw materials with the compost accelerator, as well as to their colonization with insect populations. Additionally, the nitrogen content of the mature compost was 2.65% and very close to that of the initial mixture (2.26%) (Table 2). This reveals that during the composting process no nitrogen losses—which could have been caused by the nitrification of nitrate to nitrite and the evaporation of ammonia nitrogen—took place. According to Hao and Benke [24] the main form of N lost during composting is ammonia emission ranging from by 13% to 70%. The same authors reported that this wide variations appeared because of the differences in the properties of the raw material used, environmental conditions, and compost management practices. Zhu [25] composted swine manure and rice straw. They concluded that a lower initial C/N ratio of 20 by raw material
caused a higher N loss by 8% than that C/N ratio 25 caused. Additionally, Wong et al. [26] found that the use of zeolite in composting process appears promising since zeolite leads to the adsorption and precipitation of ammonia. Findings of Wong et al. [26] might partially explain the lack of nitrogen losses observed in our study. Generally, in our study, factors like the initial C/N ratio 19.5, the preservation of temperature above 60–65 °C, and the use of zeolite among raw material might be contributed to the lack of nitrogen losses during composting.

Temperature and relative humidity in 2017 were slightly lower than 2018 (Table 1). However, these differences are rather marginal and cannot possibly induce any significant changes in the morphophysiological and quality traits of the rice plants between the two years.

Generally, the statistical analysis of the growth and physiological traits showed significant effects because of the years (Y), the compost treatment (T), and in some cases, their interactions (Tables 4 and 5). Nevertheless, statistical analysis of the quality traits of rice indicated that, in most cases, the effect of the year, the compost treatment, and their interaction were non-significant (Table 5).
Table 4. Analysis of variance (one factor randomized complete block design combined over years) of the agronomic and physiological traits as influenced by the compost treatments.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>PH42</th>
<th>PH60</th>
<th>PH80</th>
<th>BT85</th>
<th>BTM</th>
<th>CCI32</th>
<th>CCI42</th>
<th>CCI62</th>
<th>CCI90</th>
<th>CCI105</th>
<th>QY32</th>
<th>QY62</th>
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</table>

CV, coefficient of variation; df, degree of freedom; NS, nonsignificant; * p < 0.05 level of significance; ** p < 0.01 level of significance; PH42, PH60, PH80: plant height at 42, 60, 80 DAS (days after sowing); BT85, BTM: biomass total at 85 DAS and at maturity; CCI32, CCI42, CCI62, CCI90, CCI105: chlorophyll content index at 32, 42, 62, 90, and 105 DAS; QY32, QY62, QY90, QY105: quantum yield at 32, 62, 90, and 105 DAS; yield: grains yield at maturity; p for Year (Y) p = 0.0557.

Table 5. Analysis of variance (one factor randomized complete block design combined over years) of the agronomic, qualitative, and physico-chemical traits as influenced by the compost treatments.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
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<th>NGM</th>
<th>TMY</th>
<th>WMY</th>
<th>PL</th>
<th>PW</th>
<th>PR</th>
<th>BL</th>
<th>BW</th>
<th>BR</th>
<th>WL</th>
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<th>100GW</th>
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CV, coefficient of variation; df, degree of freedom; NS, nonsignificant; * p < 0.05 level of significance; ** p < 0.01 level of significance; HI: harvest index; NGM: % nitrogen at grains at maturity; TMY: total milling yield, WMY: whole milling yield; PL, PW, PR: paddy rice length, width, and length/width ratio; BL, BW, BR: brown rice length, width and length/width ratio; WL, WW, WR: white rice length, width, and length/width ratio; 100GW: weight of 100 grains; CH: % chalkiness; AMY: % amylose.
Concerning the plant height, the ANOVA indicated that rice height at 42, 60 and 80 DAS was affected by the year (Y), the compost treatment (T), and their Y × T interactions (Table 4). Thus, mean values are presented separately for each year in Figure 3a and 3b, respectively. For the same reason (ANOVA in Table 4), the total dry aboveground biomass at 85 DAS is presented separately for each year Figure 4a,b. In the 2017 experiment and at 42, 60, and 80 DAS, the compost application in paddies resulted in significantly higher (8%–46% average increase in height) and heavier (32%–70% average increase in dry aboveground biomass) plants compared to those of the control treatment Figures 3a and 4a. Similar but more pronounced results were obtained in the 2018 experiment, since at 42, 60, and 80 DAS the compost application resulted in significant higher (8%–64%) and heavier (77%–113%) plants compared to those of the control treatment Figures 3b and 4b.

**Figure 3.** Height of rice plants (means ± se) grown in differently fertilized soil at 42, 60, and 80 days after the sowing (DAS) of the experiment during 2017 (a) and 2018 (b). Treatments contain compost application of (i) 80 kg ha⁻¹ N in split application (C1), (ii) 160 kg ha⁻¹ N in split application (C2), (iii) 320 kg ha⁻¹ N in split application (C3), (iv) 160 kg ha⁻¹ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha⁻¹ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at p < 0.05. Different letters characterize significant differences between treatments for each DAS. Full description of the treatments examined is given in Table 3.

**Figure 4.** Total dry aboveground biomass of rice plants (means ± se) grown in differently fertilized soil at 85 days after the sowing (DAS) of the experiment during 2017 (a) and 2018 (b). Treatments contain compost application of (i) 80 kg ha⁻¹ N in split application (C1), (ii) 160 kg ha⁻¹ N in split application (C2), (iii) 320 kg ha⁻¹ N in split application (C3), (iv) 160 kg ha⁻¹ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha⁻¹ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at p < 0.05. Different letters characterize significant differences between treatments. Full description of the treatments examined is given in Table 3.

In 2017 and at all DAS (except at maturity), plants in C1, C2, C3, and C4 compost treatments had 78%–104% and 82%–106% of the corresponding height and biomass of CONVEN, respectively. In 2018, plants at C1, C2, C3, and C4 compost treatments had 65%–100% of the CONVEN height and
61%–73% of the CONVEN biomass. In both years, plant biomass at maturity in C3 was similar to that in the CONVEN treatment (Figure 5). Summarizing biomass results, the C3 treatment exhibited similar biomass to CONVEN throughout the season (except of 85 DAS in 2018).

Figure 5. Total dry aboveground biomass of rice plants (means ± se) grown in differently fertilized soil at maturity stage of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha\(^{-1}\) N in split application (C1), (ii) 160 kg ha\(^{-1}\) N in split application (C2), (iii) 320 kg ha\(^{-1}\) N in split application (C3), (iv) 160 kg ha\(^{-1}\) N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha\(^{-1}\) nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at \(p < 0.05\). Different letters characterize significant differences between treatments. Full description of the treatments examined is given in Table 3.

The application of the C3 compost treatment had the most pronounced effect on plant biomass at maturity over the application of recommended inorganic fertilizer (CONVEN). In most cases, maximum plant height was observed in the C3 and CONVEN treatments. The increase in plant height and biomass is arguably attributed to the enhanced nutrient level induced in the soil by the compost, which leads to the continuous assimilation of nutrients in available forms by the plants (or to a slow release fertilization). This hypothesis for the positive effect of compost in plant height and biomass has also been made by other researchers [27,28].

Concerning the physiological traits, the results showed significant Y × T interaction for CCI, with the exception of 62 DAS showing significant difference only for T factor (Table 4). Thus, the mean values for each compost treatment are presented separately in Figure 6. The CCI values ranged between 5.3 and 6.9 at 32 DAS, 12.9 and 16.5 at 62 DAS, 17.9 and 26.7 at 90 DAS, and 11.6 and 17.1 at 105 DAS. The CCI showed an increase during the season up to 90 DAS—as the plants were growing—and an expected decline at 105 DAS, since the plants entered the maturity phase. Generally, the CCI in C3 was similar or higher (18% at 32 DAS) compared to the CONVEN treatment (Figure 6). Similarly, the CCI in C1, C2, and C4 was similar to the CONVEN one at 32 DAS, but lower by 12% to 23% at 62, 92, and 105 DAS. Based on the phenological growth/BBCH stages, the mean CCI values in the current study for the tillering stage, booting stage, filling stage, and maturity stage were 6.0, 16.9, 23.0, and 14.2, respectively. In accordance, Liu et al. [29] concluded that at the same growth stages the median CCI values were 21.1, 43.1, 41.1, and 18.9, respectively. In both studies, the CCI values followed the same trend: a growth path until the filling stage and then a decrease until the maturity stage. Nevertheless, for the same growth stages, the CCI values were quite lower in our study. According to Peng et al. [30], CCI is a good indicator for the evaluation of compost effects on rice cultivation, whereas chlorophyll meters can be used for monitoring leaf nitrogen status in rice, since rice plants with higher nitrogen content have higher chlorophyll content and consequently higher CCI values [31]. Chlorophyll provides an indication of the nutritional status as a result of nitrogen absorption and utilization, which serves as a reliable means to estimate the function of the nitrogen fertilizer [29] and this is confirmed from our results.
Quantum yield (QY) from 32 to 105 DAS was mainly affected by the compost treatment (T) (Table 4). Thus, the mean values for each compost treatment are presented separately at different DAS in Figure 7. Plants exhibited similar QY across the different treatments, except in the cases of 90 and 105 DAS. More specifically, at 90 DAS plants treated with compost had up to 7% higher QY than the CONVEN, whereas at 105 DAS only plants at C3 had 7% higher quantum yield compared to CONVEN.

Figure 6. Chlorophyll content index (CCI) of rice plants (means ± se) grown in differently fertilized soil at 32, 42, 62, 90, and 105 days after the sowing (DAS) of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha$^{-1}$ N in split application (C1), (ii) 160 kg ha$^{-1}$ N in split application (C2), (iii) 320 kg ha$^{-1}$ N in split application (C3), (iv) 160 kg ha$^{-1}$ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha$^{-1}$ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at $p < 0.05$. Different letters characterize significant differences between treatments for each DAS. Full description of the treatments examined is given in Table 3.

Figure 7. Quantum yield of rice plants (means ± se) grown in differently fertilized soil at 32, 62, 90, and 105 days after the sowing (DAS) of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha$^{-1}$ N in split application (C1), (ii) 160 kg ha$^{-1}$ N in split application (C2), (iii) 320 kg ha$^{-1}$ N in split application (C3), (iv) 160 kg ha$^{-1}$ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha$^{-1}$ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at $p < 0.05$. Different letters characterize significant differences between treatments for each DAS. Full description of the treatments examined is given in Table 3.
Regarding the yield, the effect of compost treatment and the $Y \times T$ were significant (Table 4). For this reason, the means presented in Figure 8a,b are not averaged across years, in order to investigate the effect of year on the yield of different treatments. C2 and CONVEN in 2017, which received similar N units, resulted in very similar yields, 7.5 Mg ha$^{-1}$ and 7.3 Mg ha$^{-1}$, respectively. Additionally, yield obtained by C1 (half N dose) was significantly lower ($-12\%$) than that of CONVEN and C3 (double N dose) exhibited significantly higher ($19\%$) yield compared to the CONVEN treatment Figure 8a. Similar results were observed in 2018, where the yield of C2, C3, and C4 did not differ significantly compared to the CONVEN one (6.3–6.9 Mg ha$^{-1}$) Figure 8b. In conclusion, C2 and C3 showed a more consistent behavior across the two years of experimentation compared to the other treatments. Siavoshi and Laware [32] reported that 4 Mg ha$^{-1}$ of an organic fertilizer comprising 25% of rice straw and husks and 75% by cow and poultry manure increased the yield by 19% (4.7 Mg ha$^{-1}$). In the present study, the application of 3.0 Mg ha$^{-1}$ of compost (C1 treatment) increased the yield to 28.5% compared to the CONTR (untreated). However, we decided to focus the discussion on the comparison with the conventional fertilization treatment, in order to give a more complete view of the use of the natural fertilizer instead of the synthetic ones. From this point of view, the addition of 6.0 Mg ha$^{-1}$ of compost (C2 treatment) in the soil produced similar yield with that of the CONVEN treatment. The application of 6.0 Mg ha$^{-1}$ of compost to the soil led to an impressive yield increase in both years, $38\%$ in 2017 and $66\%$ in 2018 compared to the CONTR. We hypothesized that these increases appeared because of the improvement in soil fertility because of compost incorporation and most likely because of its main components RH and RB, specifically. Moreover, the used compost had a low C/N ratio (9.5), potentially able to drive a fast release of mineral nitrogen into the soil. The effectiveness of RH in compost and in biofertilizer production is well documented. Pode [33] refers that the fertilization of paddy fields with RH ash waste increases the concentration of silicic acid in the soil, yielding a rich harvest of rice. Similarly, Mohamed et al. [34] found that RH are a renewable source for the production of zeolite, which is used as a soil amendment.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Yield of rice plants (means ± se) grown in differently fertilized soil of the experiment during 2017 (a) and 2018 (b). Treatments contain compost application of (i) 80 kg ha$^{-1}$ N in split application (C1), (ii) 160 kg ha$^{-1}$ N in split application (C2), (iii) 320 kg ha$^{-1}$ N in split application (C3), (iv) 160 kg ha$^{-1}$ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha$^{-1}$ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at $p < 0.05$. Different letters characterize significant differences between treatments. Full description of the treatments examined is given in Table 3.}
\end{figure}

The HI was affected by the compost treatment (Table 5). The HI of C1, C2, and C4 was similar, whereas the HI of CONVEN was significantly lower (Figure 9), because of their higher biomass rate at maturity. The HI of C3 did not differ from the respective of C2 and CONVEN. This means that these treatments resulted in biomass increases, but without a significant yield increase.
whereas N in C1 and C4 were 12% and 16% lower, respectively, compared to CONVEN.

Figure 10. Percentage nitrogen at grains (means ± se) harvested by rice plants grown in differently fertilized soil of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha$^{-1}$ N in split application (C1), (ii) 160 kg ha$^{-1}$ N in split application (C2), (iii) 320 kg ha$^{-1}$ N in split application (C3), (iv) 160 kg ha$^{-1}$ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha$^{-1}$ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at $p < 0.05$. Different letters characterize significant differences between treatments. Full description of the treatments examined is found in Table 3.

The N concentration in rice grains was affected by the treatment and by Y × T interactions (Table 5, Figure 10). The C2, C3, and CONVEN treatments resulted in similar nitrogen concentration in grains, whereas N in C1 and C4 were 12% and 16% lower, respectively, compared to CONVEN.

Figure 9. Harvest index (HI) (means ± se) of rice plants grown in differently fertilized soil of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha$^{-1}$ N in split application (C1), (ii) 160 kg ha$^{-1}$ N in split application (C2), (iii) 320 kg ha$^{-1}$ N in split application (C3), (iv) 160 kg ha$^{-1}$ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha$^{-1}$ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at $p < 0.05$. Different letters characterize significant differences between treatments. Full description of the treatments examined is given in Table 3.

In terms of the quality traits, the analysis of PW, BW, BR, WW, and WR indicated that the effect of compost treatment was significant, whereas the Y × T interaction was significant only for WW
(Table 5). Therefore, the mean values presented in Figure 11a–c are averaged across years. In most cases, a constant trend was observed and this was rather expected, since these traits are varietal and it is very unlikely to observe big differences by simply altering the fertilization treatment. Nevertheless, at C3 treatment the width of paddy, brown and white rice grains presented the lowest values—albeit not statistically significant in some cases—whereas the length/width ratio of brown and white rice grains exhibited the highest values and they differed significantly from the CONVEN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>LSDPW</th>
<th>LSDBW</th>
<th>LSDBR</th>
<th>LSDWW</th>
<th>LSDWR</th>
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</thead>
<tbody>
<tr>
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<td>0.03</td>
<td>0.08</td>
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Figure 11. Width of paddy (PW), width (BW) and length/width ratio (BR) of brown, and width (WW) and length/width ratio (WR) of white rice grains (means ± se), harvested of rice plants grown in differently fertilized soil of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha⁻¹ N in split application (C1), (ii) 160 kg ha⁻¹ N in split application (C2), (iii) 320 kg ha⁻¹ N in split application (C3), (iv) 160 kg ha⁻¹ N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha⁻¹ nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at \( p < 0.05 \). Different letters characterize significant differences between treatments for each parameter. Full description of the treatments examined is given in Table 3.

With respect to 100GW, TMY, and WMY no differences were observed across the years, compost treatments, and \( Y \times T \) interaction (Table 5). Milling yield, which is a very important parameter tightly connected with the value of the rice commodity in the industry, did not exhibit any significant differences among the different fertilization treatments. Thus, it is safe to conclude that the use of the compost did not underrate the commodity value. This contradicts with the findings of McClung [35], who concluded that cultural management methods like fertilization can affect the quality parameters such as total and whole milling yield. It is noteworthy that the grain CH was affected by the compost treatment (Table 5) and in C3 it was significantly lower (28%) than the respective one in CONVEN, whereas C1 and C2 resulted in 15% to 21% lower—albeit not statistically significant—CH (Figure 12). Finally, AMY did not differ significantly among all treatments (Table 5).
was performed in 2016, during the preliminary phase of our study [37]. The results revealed that taking into consideration that, at least presently, the complete replacement of chemical fertilizers with eco-friendly alternatives in the future. This kind of compost reported in the present study can be considered suitable for the rice crop nutrient requirements even from the first year of application. In contrast, Moe et al. [36] refer that organic fertilizers (like compost made from kitchen waste and bamboo) with total N < 4% were only effective at improving rice growth and yield in the second year, after being continuously applied for 2 years. In order to understand the socio-economic implications of the use of the novel compost, a cost analysis for its production was performed in 2016, during the preliminary phase of our study [37]. The results revealed that the proposed compost has the potential to increase the gross value of rice production, specifically, in organic farming systems. However, compost production and application cannot always improve both the economic and social impacts at the same time. Although some of the compost treatments resulted in similar soil fertility rates, which are eco-friendly, more technological interventions (such as the enrichment of raw material with materials of high potential in N units) are required to make it as effective as the conventional fertilization, so that rice growers can be motivated to adopt such eco-friendly alternatives in the future. This kind of compost reported in the present study can be also developed in small scale rice farming systems, aiming sustainability through circular economy principals, by reducing the cultivation costs and the environmental footprint of the rice cultivation. Taking into consideration that, at least presently, the complete replacement of chemical fertilizers with composts in crops may not be a realistic idea in the conventional cropping systems, the results of this study reveal that the proposed compost has a potential to be used as a supplementary in paddies in smaller farming systems, or in greenhouse or vegetable-based cultivations.

In case of paddies, precision agriculture could be the used for compost application according to field variability and site-specific conditions [38]. Concerning the application of the novel compost in the field, nowadays, many companies have started to develop special spreaders of natural fertilizer and composts that can apply those amounts and particle types. Moreover, there are cases where these spreaders are GPS- and computer-driven (variable rate applicators) [39–43]. Thus, it is expected that in the near future more suitable equipment will be available in the market.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Percentage of grain chalkiness (%)</th>
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<tr>
<td>C1</td>
<td>14 ± 2</td>
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<tr>
<td>C2</td>
<td>12 ± 2</td>
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<tr>
<td>C3</td>
<td>10 ± 2</td>
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<tr>
<td>C4</td>
<td>8 ± 2</td>
</tr>
<tr>
<td>CONTR</td>
<td>6 ± 2</td>
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<tr>
<td>CONVEN</td>
<td>4 ± 2</td>
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Figure 12. The percentage of grains with chalkiness (means ± se) of grains harvested of rice plants grown in differently fertilized soil of the experiments during 2017 and 2018. Treatments contain compost application of (i) 80 kg ha\(^{-1}\) N in split application (C1), (ii) 160 kg ha\(^{-1}\) N in split application (C2), (iii) 320 kg ha\(^{-1}\) N in split application (C3), (iv) 160 kg ha\(^{-1}\) N in single application (C4), (v) an untreated control (CONTR), and (vi) 160 kg ha\(^{-1}\) nitrogen chemical fertilizer (CONVEN). Means were compared by the Bonferroni adjusted LSD value at \(p < 0.05\). Different letters characterize significant differences between treatments for each parameter. Full description of the treatments examined is given in Table 3.

Summarizing, the results of the study indicated that the application of the proposed compost at the rate of 6 Mg ha\(^{-1}\) can be considered sufficient for the rice crop nutrient requirements even from the first year of application. In contrast, Moe et al. [36] refer that organic fertilizers (like compost made from kitchen waste and bamboo) with total N < 4% were only effective at improving rice growth and yield in the second year, after being continuously applied for 2 years. In order to understand the socio-economic implications of the use of the novel compost, a cost analysis for its production was performed in 2016, during the preliminary phase of our study [37]. The results revealed that the proposed compost has the potential to increase the gross value of rice production, specifically, in organic farming systems. However, compost production and application cannot always improve both the economic and social impacts at the same time. Although some of the compost treatments resulted in similar soil fertility rates, which are eco-friendly, more technological interventions (such as the enrichment of raw material with materials of high potential in N units) are required to make it as effective as the conventional fertilization, so that rice growers can be motivated to adopt such eco-friendly alternatives in the future. This kind of compost reported in the present study can be also developed in small scale rice farming systems, aiming sustainability through circular economy principals, by reducing the cultivation costs and the environmental footprint of the rice cultivation. Taking into consideration that, at least presently, the complete replacement of chemical fertilizers with composts in crops may not be a realistic idea in the conventional cropping systems, the results of this study reveal that the proposed compost has a potential to be used as a supplementary in paddies in smaller farming systems, or in greenhouse or vegetable-based cultivations.

In case of paddies, precision agriculture could be the used for compost application according to field variability and site-specific conditions [38]. Concerning the application of the novel compost in the field, nowadays, many companies have started to develop special spreaders of natural fertilizer and composts that can apply those amounts and particle types. Moreover, there are cases where these spreaders are GPS- and computer-driven (variable rate applicators) [39–43]. Thus, it is expected that in the near future more suitable equipment will be available in the market.
Finally, further research is needed in the direction of improving the compost, particularly by increasing the N content, in order to improve its effectiveness and consequently permit the application of smaller amounts of compost into the cropping system.

4. Conclusions

In the current study an innovative approach is proposed to exploit the rice milling industrial by-products toward a more sustainable rice farming system with care to the environmental footprint reduction. The novel formulation serves the principals of the circular economy and, at the same time, it could be a valuable solution for sustainable organic farming systems. According to our results, the application of 6.0 Mg ha\(^{-1}\) of compost into paddies can be considered sufficient for the rice crop nutrient requirements, without compromising yield and quality of the rice commodity.


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

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