agronomy

Review

A Review of the Influence of Genotype, Environment, and Food Processing on the Bioactive Compound Profile of Red Rice (*Oryza sativa* L.)

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Abstract: Red rice has achieved a lot of visibility due to its greater amounts of bioactive compounds compared to traditional white rice. The increased recognition of red rice by the industry is a consequence of the expansion of its study in the field of research. The red color of its grains is characteristic of the presence of proanthocyanidins, which is associated with health benefits such as reducing the risk of chronic diseases. In addition, red rice is gluten-free and hypoallergenic, which makes it suitable for celiac or gluten-intolerant patients. However, the contents of phytochemicals can vary with the influence of the adaptability of genotypes to the environment, cultivation practices, abiotic stresses, and industrial processing. In this scenario, one of the challenges is to increase the diversity of red rice products while having a minimum impact on the content of bioactive compounds, mainly flavonoids and phenolic acids. In this review, a complete overview of the importance of pigmented red rice is presented, including the effects of different genotypes, the growth environment, and industrial processing on the bioactive compounds, mainly flavonoids and phenolic acids, in red rice, and the health benefits of its products are described. Studies cited in this review article were found by searching through the Web of Science database from 2013 to 2023. After a detailed and up-to-date search, 36 studies were included in this review article.

Keywords: phenotype; pigmented rice; proanthocyanidins; health

Citation: Rodrigues, L.A.; Cañizares, L.d.C.C.; Meza, S.L.R.; Peres, B.B.; Jappe, S.N.; Timm, N.d.S.; Oliveira, M.d.; Coradi, P.C. A Review of the Influence of Genotype, Environment, and Food Processing on the Bioactive Compound Profile of Red Rice (*Oryza sativa* L.). *Agronomy* **2024**, *14*, 616. https://doi.org/10.3390/agronomy14030616

Received: 20 February 2024
Revised: 9 March 2024
Accepted: 13 March 2024
Published: 19 March 2024

1. Introduction

In traditional rice crop growing, red-pigmented rice (*Oryza sativa*) was categorized as an invasive plant and its cultivation was not performed for human consumption. However, as science advanced in its investigations into red rice, it was found that red-pigmented rice contains high levels of nutritional and functional components [1]. In 2014, a new variety of red-pigmented rice (*O. sativa* var. SCS 119 Rubi) was developed for specialty rice markets in Brazil [2]. The annual production of red rice is around 10,000 tons per year in Brazil, and it is consumed mainly in an unpolished or partially polished form [3].

The consumption of red-pigmented rice has been increasing due to the new healthy eating trend of the world's population, given that its consumption has numerous health benefits related to reducing the risk of chronic diseases [4]. Red rice has a larger number of bioactive compounds—mainly flavonoids and phenolic acids—when compared to traditional brown rice, which shows biological activities such as antioxidant, antimicrobial, anticancer, anti-inflammatory, and anti-allergic activities [5]. The main flavonoid antioxidant group found in red rice is proanthocyanidins, which is responsible for the red color of its pericarp [5].

New food products are being formulated based on red rice, such as crispy rice, rice cookies, rice flour, noodles, malt, and fermented wine. This is not only due to its nutritional properties but also due to its sensory characteristics, such as its characteristic red color and nutty flavor [6]. In addition, it is important to highlight that red rice is gluten-free and hypoallergenic, showing gel stability in freezing or thawing conditions and revealing resistance to acidic ingredients. These aspects contribute to several applications in the food industry [7,8].

On the other hand, the variation in the levels of bioactive compounds is mainly related to the external influences of the cultivation environment, as well as the genotype used in the cultivation [8]. The adaptability of genotypes to the environment, cultivation practices, and other stresses (water, saline, and temperature) can influence the biosynthesis of bioactive compounds [9]. In addition, the processing of these grains in the food industries can contribute to a reduction in phytochemicals, mainly due to the thermal processes to which they are subjected [10]. However, new techniques for processing these grains in the industry can aid retention or increase the quantity of these compounds, such as germination and irradiation UV-C [11]. Despite that, no review articles were found that focused on revealing the impact of the type of genotype, cultivation environment, pre-processing, and industrial processing on the phytochemical composition of red-pigmented rice, with more comprehensive studies required on this subject. In addition, the demand for new nutritious food products has grown worldwide due to the need to feed a growing world population. Increased concerns about the consumption of healthier foods, sustainability, and environmental impact are also addressed by this development since red rice can be used in its entirety, reducing the waste generated from its use. In this regard, the present review provides a comprehensive report on the current literature about the influence of genotype, environment, and food processing on bioactive compounds, including flavonoids, proanthocyanidins, and phenolic acids found in red-pigmented rice.

2. Review Structure

This article reviewed the main results presented in the up-to-date literature about the influence of genotype, growth environment, industrial pre-processing techniques such as drying, storage, and polishing, and industrial processing methods such as cooking, baking, and extrusion on the profiles of bioactive compounds in red rice grains, such as flavonoids, proanthocyanidins, and phenolic acids, and their health benefits. The studies cited in this review article were found by searching through the Web of Science database for articles dated from 2013 to 2024. The keywords and phrases used in the search included the following: "red rice genotypes", "effect of environment on phytochemicals in red rice", "effect of genotype on phytochemicals in red rice", "bioactive compounds in red rice", "effect of industrial processing on phytochemicals in red rice", "red rice drying", "red rice storage", "red rice polishing", "red rice cooking", "red rice baking", "red rice extrusion", "red rice products", "food products based on red rice", and "health benefits of red rice". The articles used in this review were selected from journals with a high impact factor. Initially, more than 100 scientific articles were read. After careful selection, 38 studies were included in this review article. The selected articles have relevance to science and display reliability in their data. In addition, a geographical distinction was made in relation to the scientific reports cited in this review (Figure 1). For a better understanding of the studies presented in this review article, table in Section 4 was drawn up, showing the main results in relation to the influence of the genotype, environment, and processing on bioactive compounds, and Figure 2 shows where these compounds are located in the structure of red rice, highlighting its main phytochemical composition.

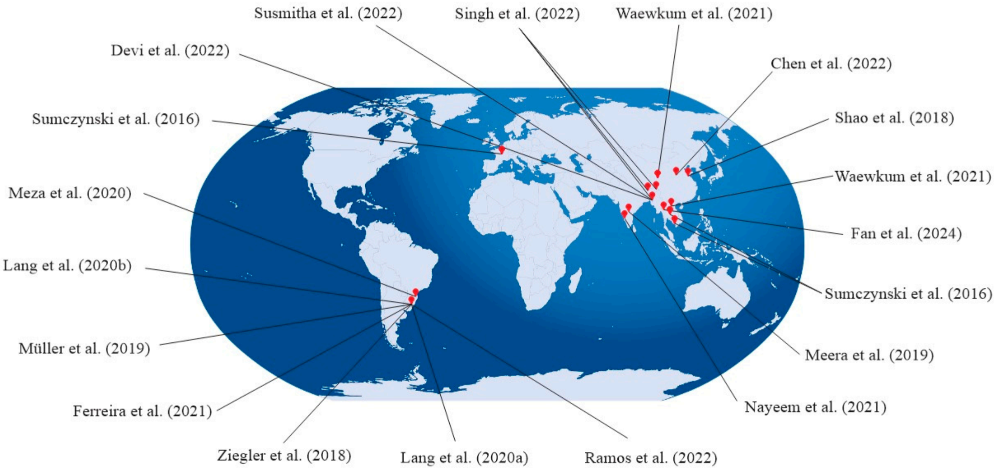

Figure 1. Geographic distinction of the studies discussed in this article review. (Lang et al., 2020a [1]; Chen et al., 2022 [4]; Müller et al., 2021 [5]; Meza et al., 2021 [7]; Singh et al., 2022 [8]; Ziegler et al., 2018 [10]; Ferreira et al., 2021 [11]; Shao et al., 2018 [12]; Sumczynski et al., 2016 [13]; Meera et al., 2018 [14]; Susmitha et al., 2022 [15]; Ramos et al., 2022 [16]; Waewkum et al., 2021 [17]; Devi et al., 2022 [18]; Nayeem et al., 2021 [19]; Lang et al., 2020b [20]; Fan et al., 2024 [21]).

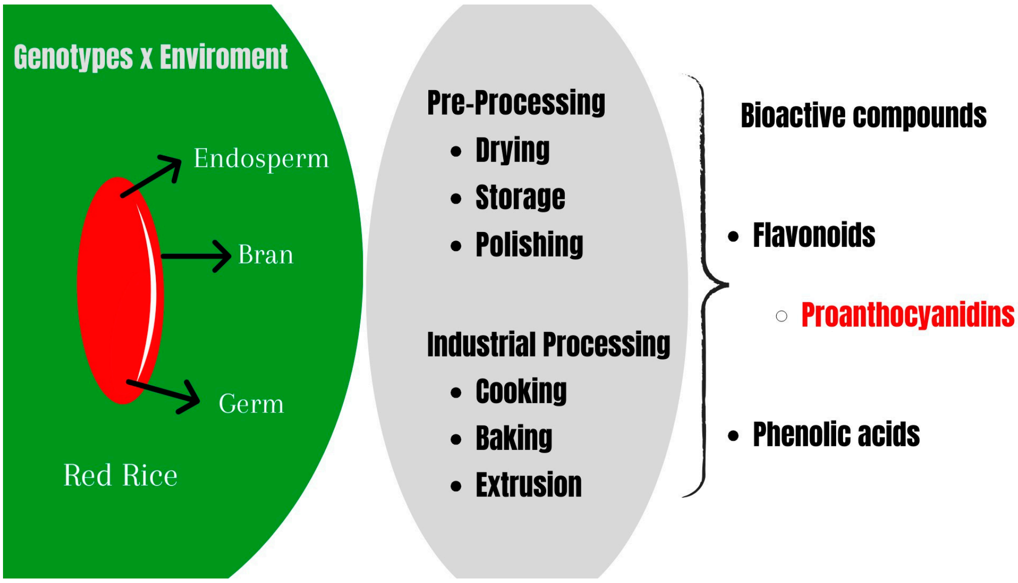

Figure 2. Overview of the influence of genotype, environment, and processing on phytochemicals, mainly proanthocyanidins, in red rice grains.

3. The Role of Different Red Rice Genotypes and Growth Environments in the Phytochemical Profile

The main biochemical compounds present in red rice are flavonoids and phenolic acids. Among the flavonoids, proanthocyanidins are the main source. Proanthocyanidins show a high molecular weight, consisting of flavan-3-ol units, with an average degree of polymerization from 2 to 14 [22]. In addition to these compounds, the phenolic acids found in red rice grains are protocatechuic acid, sinapitic acid, vanillic acid, p-coumaric acid, caffeic acid, and ferulic acid [23]. This topic will discuss the most recent studies about the effects of genotype and environment on bioactive compounds such as flavonoids and phenolic acids.

The contents of phenolic compounds, flavonoids, and antioxidant capacity in different genotypes of red rice (Hongnuo, Bianduhongmi, Hongcaomi, Hongxiangmi, Yueyahongmi, Jingganghongmi, and Sikoutianyoujihongmi) grown in Chengdu city, China, were evaluated by Chen et al. [4]. The total phenolic compounds were found to be 1.45 and 2.69 mg GAE g^{-1} in the Hongnuo and Hongxiangmi genotypes, respectively, showing statistically significant differences. For the total flavonoid content, 0.94 and 1.31 mg RE g^{-1} were found when analyzing the Jingganghongmi and Hongxiangmi genotypes, respectively, also presenting statistically significant differences. Regarding the content of individual phenolic compounds, the highest values of catechin (6.13 mg kg^{-1}) and epicatechin (1.43 mg kg^{-1}) were observed in the Yueyahongmi genotype. Among the flavonoids and phenolic acids, the highest value of dihydromyricetin (7.39 mg kg^{-1}) was found in the Sikoutianyoujihongmi genotype, while the highest values of quercetin (2.60 mg kg^{-1}), naringin (2.58 mg kg^{-1}), ferulic acid (1.03 mg kg^{-1}), and trifoline (22.97 mg kg^{-1}) were found in the Hongnuo genotype. The antioxidant capacity measured by the ORAC assay ranged from 80.60 to 113.45 µmol Trolox g^{-1} in the Yueyahongmi and Sikoutianyoujihongmi genotypes, respectively, showing statistically significant differences. Additionally, the authors performed a correlation analysis, verifying a positive correlation between the content of phenolic compounds and flavonoids with antioxidant activity for all genotypes analyzed.

Shao et al. [12] analyzed the contents of phenolic acids, anthocyanins, proanthocyanidins, and antioxidant capacity of the red rice genotypes (Jinggangshanhongmi, Xiangwanxian, Qianxiuhong, Changhong, and Hongmi) grown in Jinan, China. The contents of the total flavonoids were 1.62 and 3.83 mg CE g^{-1}, while proanthocyanidins were 0.58 and 2.54 mg CE g^{-1} for the Jinggangshanhanhongmi and Hongmi genotypes, respectively, showing statistically significant differences. For free phenolic acids, a range from 1.76 to 1.56 µg g^{-1} was observed for p-coumaric acid, from 1.32 to 2.59 µg g^{-1} for ferulic acid, and from 0.27 to 0.82 µg g^{-1} for isoferulic acid. The radical scavenging activity of the free phenolic fraction was higher in the Hongmi genotype (0.51 mg GAE g^{-1}) and lower in the Jinggangshanhongmi genotype (0.06 mg GAE g^{-1}) compared to the other genotypes, respectively, showing statistically significant differences.

Singh et al. [8] studied the influence of the growing environment on the contents of total phenolic, flavonoid, anthocyanin, and antioxidant capacity of red rice genotypes as follows: Lumre, Tsulu tsuk (Nagaland, India), Aamda, Tasung (Arunachal Pradesh, India), Kawnglawng, Fazu (Mizoram, India), and Menil mibabaret (Meghalaya, India). The contents of total phenolic compounds were 4.87 and 9.00 mg GAE g^{-1} in the Lumre and Aamda genotypes, respectively, showing statistically significant differences. The levels of total flavonoids ranged from 0.33 to 2.86 mg QE g^{-1} in the Menil mibabaret and Tasung genotypes, respectively, also showing statistically significant differences. Regarding the antioxidant capacity measured by the DPPH assay, the highest result was found in the Kawnglawng genotype (97.69%) and the lowest in the Aamda genotype (52.23%), showing statistically significant differences and highlighting the influence of environmental and genotypic characteristics on red rice phytochemicals.

To further elucidate the influence of the growing environment on the biosynthesis of bioactive compounds in red rice, another study analyzed the total phenolic compounds, flavonoids, and antioxidant activity in traditional red rice and aromatic jasmine red rice cultivated in France, Cambodia, and Thailand [13]. The highest levels of phenolic compounds and flavonoids were found in traditional and aromatic red rice produced in Thailand (3708 mg GAE kg^{-1} and 2057 mg RE kg^{-1}, respectively). In contrast, the lowest values were observed in both red rice varieties produced in France (1538 mg GAE kg^{-1} and 822 mg RE kg^{-1}, respectively), showing statistically significant differences. The results of the phenolic compounds were correlated with the antioxidant activity. The highest antioxidant activity in the free fraction was found in rice produced in Thailand (15.9 mmol TEAC kg^{-1}) and the lowest in red rice produced in France (6.6 mmol TEAC kg^{-1}). However, for the major individual phenolic compounds, the highest contents of protocatechuic acid (30.2 mg kg^{-1}), catechin (44.0 mg kg^{-1}), and trans-p-coumaric acid (3.7 mg kg^{-1}) were found in red rice produced in France. Moreover, Meera et al. [14] analyzed the content of phenolic compounds, flavonoids, and antioxidant capacity in the red rice Kavuni genotype produced in Tamilnadu, India. The authors reported contents of 5.89 mg GAE g^{-1}, 84.40 mg CE g^{-1}, and 99.52% for the total phenolic content, total flavonoids, and antioxidant capacity measured by the DPPH assay, respectively.

After a thorough analysis of the studies, it was possible to observe a significant variability in the levels of phytochemicals in red rice, which directly influences the antioxidant capacity of the grains. The main differences are associated with the contents of flavonoids and phenolic acids, influenced by environmental and genotypic factors. These factors lead to stress responses during cultivation, which may improve the biosynthesis of bioactive compounds and the genetic specificity of each red rice genotype [4,15,24].

4. Effect of Industrial Pre-Processing on the Bioactive Compounds in Red Rice

Some industrial pre-processing steps, such as drying, storage, and polishing, can affect the levels of bioactive compounds in red rice grains, particularly the contents of total phenolics, flavonoids, proanthocyanidins, and their antioxidant capacity. This section discusses the effects of drying, storing, and polishing red rice during pre-processing. However, the main limitations found in the studies covered in this section were the diversity of units used to express the results, the standards used in the analyses, and the methods applied to quantify the bioactive compounds and antioxidant capacity, making comparisons between studies difficult. To minimize these effects, we have standardized the results for grams of red rice in Table 1.

4.1. Drying and Storage

After harvesting, the grains are taken for storage and/or industrial processing. The first stage of grain processing is drying, which aims to reduce the moisture content of the grains to improve the quality conservation in subsequent stages. Exposure of red rice grains to high drying temperatures leads to changes in the phytochemical profile, often negatively affecting its content due to heat treatment [16]. Following the drying process, the grains are typically stored until processing. During storage, red rice grains remain metabolically active, which can result in a reduction in the quality parameters and, consequently, in the phytochemical profile of the grains [25]. This topic will discuss the most recent literature on the effects of drying and storage processes on the phytochemical profile of red-pigmented rice.

Delayed drying is defined as the period between harvest and the drying of the grains. The high moisture and temperature of the grains during this period, along with climatic differences, contribute to the loss of commercial quality of the grains [1]. Lang et al. [1] evaluated the influence of delayed drying times of 0, 3, and 6 days and temperatures of 15 and 25 °C during 12 months of storage of red rice (Jaguarão, Brazil) on the content of phenolic compounds and total proanthocyanidins. The contents of free phenolics and proanthocyanidins tended to decrease with increasing duration of the pre-drying period.

On the other hand, a reduction in the content of free phenolics (6.11 mg GAE g^{-1}) in red rice was observed at 15 °C for 12 months compared to the control (6.59 mg GAE g^{-1}). However, a drastic reduction in free phenolics (5.19 mg GAE g^{-1}) was detected after 6 days of delayed drying time during 12 months of storage at 25 °C, showing statistically significant differences. A similar trend was observed for proanthocyanidins, with a 10.5% reduction in content at 15 °C and zero days of delayed drying time for 12 months, and a 30.7% reduction in proanthocyanidins content at 25 °C and 6 days of delayed drying time for 12 months. The greater impact on the content of phenolic compounds and proanthocyanidins in red rice with 6 days of drying time at 25 °C may be associated with the antioxidant action of phenolic compounds, both in inhibiting lipid peroxidation and in chelating reactive metals. Conditions with longer drying times imply a reduction in grain quality, consequently affecting the production of bioactive compounds, including phenolic compounds and proanthocyanidins [1].

Table 1. Total phenolics, flavonoids, proanthocyanidins, antioxidant activity, and individual free phenolics of red rice exposed to different processing.

Variables	Condition	Total Free Phenolics	Total Flavonoids	Total Proanthocyanidins	Antioxidant Activity	Individual Free Phenolics (Range)	References
Delayed drying and stored at 12 months	0–6 days	6.59–5.19 mg GAE g^{-1}	-	3.13–2.17 mg CE g^{-1}	-	-	[1]
Genotypes	Hongnuo Bianduhongmi Hongcaomi, Hongxiangmi Yueyahongmi, Jingganghongmi Sikoutianyoujihongmi	1.45 a 2.69 mg GAE g^{-1}	0.94 a 1.31 mg RE g^{-1}	-	80.60 a 113.45 μmol Trolox g^{-1} (ORAC assay)	Catechin: 3.26–6.13 μg g^{-1} Epicatechin: 1.11–1.43 μg g^{-1} Ferulic acid: 0.10–1.03 μg g^{-1} Naringin: 1.31–2.58 μg g^{-1} Protocatechuic acid: 1.45–9.79 μg g^{-1} Quercetin: 1.75–2.60 μg g^{-1}	[4]
Rice cake sprouted at different times	8–40 h	0.67–1.13 mg GAE g^{-1}	0.46–1.14 mg CE g^{-1}	-	7.77–10.70 μmol TE g^{-1} (DPPH assay)	Caffeic acid: 0.54–0.78 μg g^{-1} Catechin: 1.16–2.06 μg g^{-1} Coumaric acid: 0.42–0.86 μg g^{-1} Ferulic acid: 4.52–5.86 μg g^{-1} Myricetin: 0.32–0.69 μg g^{-1} Quercetin: 0.55–4.19 μg g^{-1} Rutin: 3.19–7.39 μg g^{-1}	[5]
Snacks	-	100.21 mg GAE g^{-1}	0.99 mg CE g^{-1}	0.83 mg CE g^{-1}	3.1 mol TE g^{-1} (DPPH assay) 24.4 mol TE g^{-1} (ORAC assay)	-	[7]
Genotypes	Lumre Tsulu tsuk Aamda Tasung Kawnglawn Fazu Menil mibabaret	4.87–9.00 mg GAE g^{-1}	0.33–2.86 mg QE 100 g^{-1}	-	52.23–97.69% (DPPH assay)	-	[8]
Stored at 6 months	16–40 °C	11.3–14.6 mg GAE g^{-1}	-	0.981–0.987 mg CE g^{-1}	0.8–3.5 mg TE g^{-1}	Catechin: 2.3–4.6 μg g^{-1} Ferulic acid: 3.5–6.9 μg g^{-1} p-Coumaric acid: 0.2–0.9 μg g^{-1}	[10]

Table 1. *Cont.*

Variables	Condition	Total Free Phenolics	Total Flavonoids	Total Proanthocyanidins	Antioxidant Activity	Individual Free Phenolics (Range)	References
UV-C and stored for 6 months	0–3 h	-	-	-	-	Caffeic acid: 2.3–2.7 µg g^{-1} Coumaric acid: 5.4–6.0 µg g^{-1} Ferulic acid: 4.4–5.5 µg g^{-1} Gallic acid: 0.0–1.1 µg g^{-1} Vanillic acid: 2.7–5.5 µg g^{-1}	[11]
Genotypes	Jinggangshanhongmi Xiangwanxian 12 Qianxiuhong Changhong N^{o}. 2 Hongmi 2	-	1.62–3.83 mg CE g^{-1}	-	-	Ferulic acid: 1.32–2.59 µg g^{-1} Isoferulic acid: 0.27–0.82 µg g^{-1} p-coumaric acid: 1.76–1.56 µg g^{-1}	[12]
Location	France Cambodia Thailand	0.0076–0.0119 mg RE g^{-1}	0.0822–0.2057 mg RE g^{-1}	-	0.00159–0.00066 mmol TE g^{-1} (DPPH assay)	Caffeic acid: 19.5–25.3 µg g^{-1} Catechin: 4.2–5.7 µg g^{-1} Cinnamic acid: 0.1–1.1 µg g^{-1} Ferulic acid: 2.7–5.3 µg g^{-1} Gallic acid: 10.2–10.3 µg g^{-1} m-Coumaric acid: 0.2–0.3 µg g^{-1} Protocatechuic acid: 20.4–30.2 µg g^{-1} Quercetin: 2.3–3.4 µg g^{-1} Rutin: 1.3–3.3 µg g^{-1} Syringic acid: 1.6–2.9 µg g^{-1} trans-p-coumaric acid: 0.5–3.7 µg g^{-1} Vanillic acid: 0.5–1.2 µg g^{-1}	[13]
Idli	-	0.19 mg GAE g^{-1}	99.10 mg QE g^{-1}	-	0.11 mg FA g^{-1} (DPPH assay)	-	[15]
Drying temperature and stored for 12 months	40–100 °C	-	-	-	-	Caffeic acid: 2.39–2.50 µg g^{-1} Catechin: 4.47–4.57 µg g^{-1} Epicatechin: 2.62–2.76 µg g^{-1} Ferulic acid: 3.78–3.81 µg g^{-1} Luteolin: 1.86–1.89 µg g^{-1} p-coumaric acid: 1.69–1.73 µg g^{-1}	[16]

Table 1. *Cont.*

Variables	Condition	Total Free Phenolics	Total Flavonoids	Total Proanthocyanidins	Antioxidant Activity	Individual Free Phenolics (Range)	References
Drying temperature cooked	40–100 °C	-	-	-	-	Caffeic acid: 2.44–3.30 μg g^{-1} Catechin: 3.02–4.08 μg g^{-1} Chlorogenic acid: 4.36–8.58 μg g^{-1} Epicatechin: 4.75–4.85 μg g^{-1} Ferulic acid: 3.09–3.44 μg g^{-1} Luteolin: 1.70–2.57 μg g^{-1} p-coumaric acid: 2.05–2.07 μg g^{-1}	[16]
Flour	-	11.029 mg GAE g^{-1}	60.422 mg QE g^{-1}	-	2.538 mg TEAC g $^{-1}$ (DPPH assay)	-	[17]
Bran	-	10.62 mg GAE g^{-1}	11.22 mg QE g^{-1}	-	90.93% (DPPH assay)	-	[18]
Cooking	-	220–319 mg GAE g^{-1}	1000–1200 mg QE g^{-1}	-	-	-	[19]
Pie with transglutaminase	-	432.8 mg GAE g^{-1}	-	-	-	Caftaric acid: 0.51–0.52 μg g^{-1} Catechin: 7.05–8.93 μg g^{-1} Hydroxybenzoic acid: 9.82–11.58 μg g^{-1} p-coumaric acid: 1.72–2.05 μg g^{-1}	[20]

GAE, gallic acid equivalent; QE, quercetin equivalent; DPPH, 2,2-diphenyl-1-picrylhydrazyl; ORAC, oxygen radical absorbance capacity; CE, catechin equivalent; TE, trolox equivalent; PA, phenolic acid (mixture of gallic acid, protocatechuic acid, p-hydroxybenzoic acid, vanillic acid, p-coumaric acid, caffeic acid, ferulic acid, and chlorogenic acid); RE, rutin equivalent.

Ramos et al. [16] analyzed the effect of drying temperatures (40, 60, 80, and 100 °C) and storage times (0, 6, and 12 months) on the contents of total phenolic compounds and total proanthocyanidins in raw and cooked red-pigmented rice grains (Jaguarão, Brazil). They observed a reduction in the levels of free and bound phenolic compounds and proanthocyanidins with increasing drying temperatures and storage times. The main individual phenolic compound identified was catechin, which decreased from 4.92 µg g^{-1} (0 days and 40 °C) and 5.26 µg g^{-1} (0 days and 100 °C) to 4.47 µg g^{-1} (12 months and 40 °C) and 4.57 µg g^{-1} (12 months and 100 °C) in raw red rice. Conversely, an increase was observed in cooked red rice, from 3.02 µg g^{-1} (0 days and 40 °C) and 4.08 µg g^{-1} (0 days and 100 °C) to 4.53 µg g^{-1} (12 months and 40 °C) and 5.09 µg g^{-1} (12 months and 100 °C).

In addition, the ferulic acid contents in red rice dried at 40 °C and stored for 12 months were affected in both raw and cooked grains, with reductions of 2.33 and 6.68%, respectively. Conversely, red rice grains dried at 100 °C and stored for 12 months showed no differences in the ferulic acid content in raw samples and an increase of 6.68% in the cooked samples. The results observed for the ferulic acid content were similar to those found for the caffeic acid content at lower drying temperatures (40 °C), showing a decrease in the caffeic acid content during the storage of raw and cooked red rice. However, in red rice dried at higher temperatures (100 °C), an increase in the content of caffeic acid was observed during storage. The increase in the contents of phytochemicals with increasing drying temperature can be associated with the release of phenolic compounds bound to the matrix through thermal processes, polymerization, or transformation of other compounds into simpler phenolics [11].

Storage temperature is also a determining factor in the maintenance of metabolite compounds in red rice. Ferreira et al. [11] evaluated the effect of storage at different temperatures (16, 24, 32, and 40 °C) for 6 months on the contents of free and bound phenolic compounds, proanthocyanidins, and free radical scavenging capacity of red rice grains (Jaguarão, Brazil). A reduction in the content of free phenolic compounds was observed during storage at 40 °C, decreasing from 13.7 to 11.3 mg GAE g^{-1}. Regarding the bound phenolic compounds, no significant differences were observed (5.2 mg GAE g^{-1}) when analyzing the initial time and 6 months of storage, presenting statistically significant differences.

When the storage of red rice at 16 °C was examined, the content of phenolic compounds increased from 13.7 to 14.6 mg GAE g^{-1} over the initial and 6-month periods, respectively. The decrease in phenolic content at high storage temperatures may result from the thermal degradation of phenolics and/or their consumption in oxidative reactions [26]. The increase in the free phenolic content at reduced storage temperatures may be partially due to the hydrolysis of phenolic compounds previously esterified or etherified to cell wall components, which were previously quantified as bound phenolic compounds.

Ferreira et al. [11] also quantified individual phenolic compounds such as ferulic acid and catechin. For ferulic acid, a decrease was observed from 3.8 to 3.5 µg g^{-1} (initial and 6 months at 16 °C) and an increase from 3.8 to 6.9 µg g^{-1} (initial and 6 months at 40 °C), showing statistically significant differences. Regarding the catechin content, an increase was observed from 3.0 to 4.6 µg g^{-1} (initial and 6 months at 16 °C) and a decrease from 3.0 to 2.3 µg g^{-1} (initial and 6 months at 40 °C). The p-coumaric acid was not initially detected and remained undetected after 6 months at 16 °C.

However, after 6 months of storage at 40 °C, a p-coumaric acid content of 0.9 µg g^{-1} was detected. Regarding the content of proanthocyanidins, no significant differences were found, regardless of the storage time and temperature. In terms of antioxidant capacity, a reduction from 3.6 to 0.8 mg TE g^{-1} was observed by the ABTS assay when comparing the beginning and 6 months of storage at 40 °C, respectively. Conversely, for the red rice grains stored at 16 °C, no differences were observed in the antioxidant capacity (3.6 mg TE g^{-1}), demonstrating a positive correlation between the free phenolic compounds and the antioxidant activity of the red rice grains.

The effect of new technologies on improving or maintaining phytochemicals in red rice during storage is also under investigation. In a study by Samyor et al. [22], the impact of UV-C radiation exposure for 0, 1 and 3 h over 6 months of storage on the profile of free phenolic compounds in red rice (Pelotas, Brazil) was evaluated. There were no differences observed in the levels of gallic and coumaric acids during the 6-month storage period, regardless of UV-C exposure. However, an increase in caffeic acid content was noted with 1 h of UV-C exposure (2.6 μg g^{-1}) compared to the treatment without UV-C (2.3 μg g^{-1}). The highest vanillic acid content was found after 3 h of UV-C exposure (5.5 μg g^{-1}) compared to the treatment without UV-C (4.6 μg g^{-1}). Conversely, a reduction in ferulic acid content was observed with 3 h of UV-C exposure (from 5.5 to 4.4 μg g^{-1}), showing statistically significant differences. UV-C treatment stimulates the activity of phenylalanine ammonia-lyase, an important enzyme in the phenylpropanoid pathway responsible for synthesizing phenolic compounds [27,28].

4.2. Polishing

After the drying and storage stages, red rice grains undergo polishing processing. Rice polishing involves removing the rice bran after the husk is removed, resulting in the edible portion of the rice grain known as the endosperm. The polishing process, performed by the rice industry, aims to enhance the physical and sensory characteristics of the rice grain and provide greater storage stability [29]. However, polishing, along with drying and storage, can also impact the content of bioactive compounds in polished red rice.

Waewkum et al. [17] evaluated the contents of total phenolic compounds, flavonoids, and antioxidant activities in polished red rice (Amnat Charoen, Thailand). The total phenolic compound content was 11.03 mg GAE g^{-1}, the total flavonoid content was 60.42 mg QE g^{-1}, and the antioxidant activities were 2.54 mg TE g^{-1}, 24.99 mg Fe^{2+} g^{-1}, and 10.29 mg TE g^{-1}, as analyzed by the DPPH, FRAP, and ABTS assays, respectively, in polished red-pigmented rice.

Moreover, Devi et al. [18] characterized the contents of total phenolic compounds, flavonoids, and antioxidant activity in red rice grains and red rice bran from the ChakhaoAngangba genotype (Manipur, India). The contents of phenolic compounds were 6.58 and 10.62 mg GAE g^{-1}, flavonoids were 6.12 and 11.22 mg catechin g^{-1}, and anthocyanins were 0.17 and 0.35 mg cyanidin-3-glucoside g^{-1} in red rice grains and red rice bran, respectively, showing statistically significant differences. The antioxidant capacity by DPPH assay in the polished red rice grain was 92.62%, and in the red rice bran, it was 90.93%. The bioactive compounds, including phenolic compounds, flavonoids, and proanthocyanidins, which impart pigmentation to red rice, are primarily located in the pericarp of the grain. This localization justifies the higher levels of these compounds in rice bran.

5. Bioactive Compounds in Red Rice Products

Pigmented red rice serves as a valuable ingredient in the food industry, utilized in various food products such as cakes, cupcakes, snacks, cookies, extruded products, and breads. However, the industrial processing of these items can alter the levels of bioactive compounds present in the raw material, leading to changes in the content of total phenolics, flavonoids, proanthocyanidins, and antioxidant capacity. This change primarily results from the heating process applied during the preparation of red rice food products. This section will explore the main industrial processes to which red rice is subjected for the production of functional food products. Despite the myriad of food varieties produced by the food industry, the studies discussed in this section are limited to cooking, roasting, and extruding red rice. Therefore, further research is necessary to develop new functional products based on red rice.

5.1. Cooked Products

The cooking process can induce chemical and physical alterations in the phytochemical composition of red rice due to the thermal processing involved. This process can lead to the release of bound forms, polymerization, oxidation, and the formation of Maillard reaction products [19].

In this study, Nayeem et al. [19] evaluated the effects of cooking on different genotypes of red rice grown in Kerala, India (Navara, Red Chitteni, Red Kuruva, Kuzhiyadichan, and Madumuzhungi genotypes) on their phytochemical properties. The initial contents of the total phenolic compounds in the raw rice samples were 300 and 450 mg GAE 100 g^{-1} in the red rice Kuruva genotype and the red rice Madumuzhungi genotype, respectively, showing statistically significant differences. However, after the cooking process, a reduction in phenolic compounds was observed in all red rice genotypes. The genotypes most affected by cooking were Kuzhiyadichan and Madumuzhungi, which reduced the content of phenolic compounds by 60.22 and 50.00%, respectively, also showing statistically significant differences. On the other hand, the other genotypes, such as Red Kuruva, Navara, and Red Chitteni, were less impacted by cooking, with reductions in their contents of phenolic compounds by 26.66, 23.81, and 16.05%, respectively.

Regarding the contents of total flavonoids and proanthocyanidins, the highest content in the raw red rice grains was found in the Navara genotype (1750 mg QE 100 g^{-1}), while the lowest was in the Kuzhiyadichan genotype (850 mg QE 100 g^{-1}), showing statistically significant differences. In contrast, in the cooked red rice grains, the highest content was found in the Red Chitteni genotype (1200 mg QE 100 g^{-1}), and the lowest content was in the Kuzhiyadichan genotype (701 mg QE 100 g^{-1}), also showing statistically significant differences. In relation to the proanthocyanidin contents, the Navara genotype exhibited the highest levels in both raw (19.0 mg 100 g^{-1}) and cooked (8.31 mg 100 g^{-1}) red rice grains, while the Red Kuruva genotype showed the lowest (5.42 mg 100 g^{-1}). The reduction in these compounds after cooking is attributed to degradation caused by the heat treatment during the cooking process or by leaching into the cooking water [18].

In this study, Susmitha et al. [15] evaluated the phenolic acids, flavonoids, and antioxidant activity of two varieties of steamed (idli) red rice (Annapurna and Balam) grown in Manipur, India. After steam cooking, the contents of the total free phenolic acids were 0.06 mg g^{-1}, and free flavonoids were 0.09 and 0.08 mg g^{-1} in Annapurna and Balam, respectively. However, when the antioxidant capacity was analyzed by the DPPH assay, the Annapurna genotype showed 0.20 mg PA g^{-1}, and the Balam genotype showed 0.11 mg PA g^{-1} for grains after steam cooking (idli). These results reveal great potential for using red rice in idli production, as it exhibits a higher bioactive composition and antioxidant capacity than idli produced with brown rice.

5.2. Bakery Products

Bakery products are made from dough prepared with flour obtained from red rice grains, which contain starch as their main component. These products can be prepared using traditional cooking methods such as baking or frying or using non-traditional methods such as microwaves and infrared. The main bakery products include bread, cookies, cakes, and pies [5]. Despite the wide variety of bakery products available, few studies have focused on developing bakery products based on red rice, with most limited to the formulation of cakes and cupcakes.

Müller et al. [5] evaluated the bioactive properties of red rice (Pelotas, Brazil) germinated for 8, 16, 24, 32, and 40 h and its application in the production of cupcakes. The authors observed a significant reduction in the content of phenolics, flavonoids, and antioxidant activity by ABTS and DPPH assays in ungerminated rice compared to rice germinated for 40 h. Specifically, there was a decrease from 1.94 to 0.79 mg GAE g^{-1} and 1.06 to 0.53 mg CE g^{-1} for phenolics and flavonoids, respectively, and from 36.78 to 19.49 µmol TE g^{-1} and 26.06 to 7.77 µmol TE g^{-1} for antioxidant activity. Regarding individual free phenolic compounds, coumaric acid decreased from 0.66 to 0.42 µg g^{-1}, ferulic acid from 4.87 to 4.52 µg g^{-1}, and rutin from 9.04 to 3.19 µg g^{-1}, while myricetin increased from 0.11 to 0.32 µg g^{-1} and from 0.85 to 4.19 µg g^{-1}, comparing ungerminated rice to 40 h of germination, respectively. The reduction in phenolic compounds may be attributed to oxidative catalysis by phenol oxidase and peroxidase enzymes, leading to a decrease in phenolic compounds [5]. Conversely, an increase in γ-aminobutyric acid (GABA) was observed, rising from 1.18 to 1.86 mg 100 g^{-1}. Additionally, the quantification of GABA in the cupcake showed an increase from 1.86 to 3.66 mg 100 g^{-1}. This increase is associated with the enhanced enzymatic activity of glutamate decarboxylase, which catalyzes the decarboxylation of L-glutamic acid, resulting in GABA [5].

By-products from red rice, such as red rice bran, contain high levels of phenolic compounds. Lang et al. [20] evaluated the effect of adding transglutaminase to gluten-free cakes made with red rice flour (Capão do Leão, Brazil) on the profile of free phenolic compounds. The authors observed statistically significant differences in the levels of hydroxybenzoic acid, p-coumaric acid, catechin, and caftaric acid when comparing red rice flour, cakes without transglutaminase, and cakes with transglutaminase. The levels increased from 2.55 to 9.82 and 11.58 µg g^{-1}, 0.42 to 1.72 and 2.05 µg g^{-1}, 1.48 to 7.05 and 8.93 µg g^{-1}, and 0.46 to 0.51 and 0.52 µg g^{-1}, respectively.

In addition, Lang et al. [20] analyzed other phenolic acids, such as protocatechuic acid, ferulic acid, and caffeic acid, in cakes made with red rice flour, both with and without transglutaminase. The study revealed a reduction of 12%, 16%, and 23% in the content of protocatechuic acid, ferulic acid, and caffeic acid, respectively, in cakes prepared with transglutaminase compared to those without. However, the overall content of phenolic compounds in the cakes was only slightly affected by the addition of transglutaminase, showing a reduction of just 3% compared to cakes without transglutaminase.

Phenolic acids in red rice are primarily present in the bound fraction, potentially linked to lignin via ether bonds through their hydroxyl groups or bound to proteins and structural carbohydrates through their carboxylic group [30]. Therefore, the rise in free phenolic compounds in the cakes may be attributed to thermal hydrolysis, which enhanced the extractability of the bound compounds [31]. Regarding the reduction of phenolic compounds in cakes with transglutaminase, this may be related to increased protein–phenol interactions, as phenolic acids can form covalent and non-covalent interactions with the active site of the amine transglutaminase group [20].

In general, industrial processing reduces the content of bioactive compounds, influencing the antioxidant capacity of red rice products. This reduction mainly occurs due to the thermal process, which leads to the degradation or complexation of free compounds or losses by leaching to which grains are subjected during processing [11]. However, research is being conducted to increase the content of these compounds in products from these grains, such as germination and the use of enzymes during processing [5,20].

5.3. Extruded Products

During extrusion, changes in the chemical, phytochemical, and structural properties can vary depending on the extrusion conditions, including the moisture content of the material, screw speed, and extrusion temperature. This technology is widely used in the food industry due to the versatility and convenience of the products extruded [8]. However, only one study was found that extruded red rice flour to produce snacks.

Meza et al. [7] produced red rice snacks by extrusion and analyzed the contents of bioactive compounds. They found that the phenolic content decreased from 4.25 to 1.00 mg FAE g^{-1}, the flavonoid content decreased from 2.80 to 0.99 mg CE g^{-1}, and the proanthocyanidin content decreased from 2.82 to 0.83 mg CE g^{-1}. The antioxidant capacity also decreased after the extrusion of red rice products, as determined by the ORAC assay (from 0.066 to 0.024 mM TE g^{-1}) and DPPH assay (from 0.0064 to 0.0031 mM TE g^{-1}), showing statistically significant differences.

The reduction in phenolic levels may be due to thermal destruction or changes in their molecular structure at high extrusion temperatures. Additionally, polymerization can lead to a reduction in chemical reactivity or extractability, which may explain the lower levels of phenolics in the extrudates.

5.4. Germinated Red Rice

An effective method to boost the levels of phenolic compounds in red rice involves inducing germination. During the germination process, various compounds are synthesized, including GABA, total phenolic compounds, and amino acids [32]. Fan et al. [21] studied the changes induced by germination in anthocyanins and proanthocyanidins. They observed an initial increase in the content of proanthocyanidins up to 12 h of germination, followed by a subsequent reduction. These changes in proanthocyanidin content suggest that the germination process stimulates the synthesis of phenolic compounds.

6. Health Benefits of Red Rice Products

Red rice grains have received significant attention from nutritionists and consumers in recent years due to their high nutritional value, significant biological activity, and substantial impact on human health [33]. Red-pigmented rice contains flavonoids such as proanthocyanidins, which exhibit various biological activities, including antioxidant, antimicrobial, anticancer, anti-inflammatory, and anti-allergic properties [5].

Lee et al. [34] reported that fermented red rice is used as both a traditional medicine and food source due to its potent cholesterol-reducing effect. Their tests on mice showed that the molecule monacolin K inhibits the initial stages of cholesterol biosynthesis by deactivating 3-hydroxy-methyl glutaryl-coenzyme A (HMG-CoA) reductase. Monacolin K, also known as lovastatin, is the primary active compound in red yeast rice. It is a bioactive compound found in Monascus-fermented products, like red yeast rice, and has demonstrated cholesterol-lowering effects in humans. Monacolin K acts as a competitive inhibitor of HMG-CoA reductase, a crucial enzyme in cholesterol biosynthesis. Aside from its lipid-lowering properties, monacolin K has potential preventive effects against colon cancer, acute myeloid leukemia, Parkinson's disease, and type I neurofibromatosis [35].

Moreover, red yeast rice is utilized as a functional raw material in Korea and is incorporated into various functional health foods worldwide [36]. Currently, several health impacts associated with the consumption of red yeast rice have been proven, including anti-inflammatory, anti-obesity, anti-diabetic, and anti-osteoporotic effects. These health effects have been demonstrated in vitro, in vivo, and in clinical trials by Huang et al. [37] and Rahmani et al. [38]. It has also been reported that red yeast rice supplementation decreases total cholesterol, triglycerides, and low-density lipoprotein cholesterol while increasing high-density lipoprotein cholesterol levels [38].

7. Conclusions and Final Considerations

The increase in demand for red rice is mainly due to its nutraceutical and sensory properties, including its potential for application in the food industry. Red rice can be used to improve the nutritional, technological, and sensory qualities of various food products, which appeals to consumers who desire healthier and more functional food products. The potential biological effects of red rice are associated with the bioactive compounds, mainly flavonoids. Proanthocyanidins are the major flavonoids found in red rice, responsible for the characteristic red color of the grain and for biological activities such as antioxidant, antimicrobial, anticancer, anti-inflammatory, and anti-allergic effects. In addition, red rice does not contain gluten, making it suitable for producing hypoallergenic food products for consumers with allergies. In addition to nutritional compositions, consumers are increasingly concerned about food sourcing, including the genotype and growing conditions, as well as processing methods, such as pre-processing (drying, storage, and polishing) and industrial processing (cooking, baking, and extrusion). However, variations in the phytochemical profile of red rice can be attributed to factors such as the genotype variety, growing environment, and processing methods. The adaptability of genotypes to environmental factors, cultivation practices, and stresses such as water, salinity, and temperature can influence the biosynthesis of bioactive compounds, leading to higher levels of phytochemicals in red rice. On the other hand, processing steps such as drying, storage, polishing, and the production of food items like cooked, baked, and extruded products can alter the chemical and phytochemical profiles of red rice grains, typically resulting in a reduction in their content. In this regard, it has become necessary to incorporate new technologies, such as germination and ultraviolet radiation, to enhance the retention or preservation of phytochemicals during industrial processing.

Author Contributions: Writing (Original Draft), L.A.R.; Conceptualization, Writing (Review and Editing), and Supervision, L.d.C.C.C., S.L.R.M. and M.d.O.; Writing (Original Draft), L.A.R.; Writing (Original Draft), L.A.R., B.B.P. and S.N.J.; Writing (Review and Editing), M.d.O. and P.C.C.; Writing (Review and Editing), N.d.S.T. and P.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CAPES (Coordination for the Improvement of Higher Education Personnel), Financial Code 001; CNPq (National Council for Scientific Technological Development), Financial Code 001, 140569/2023-5; and FAPERGS-RS (Research Support Foundation of the State of Rio Grande do Sul), Financial Code 001, for funding in the research projects and the laboratories for carrying out the experiments.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the UFPel (Federal University of Pelotas) Post-Harvest Laboratory and the (LABGRÃOS) Post-Harvest, Industrialization and Grain Quality Laboratory for their contributions to the research project.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Abbreviations List

GAE: gallic acid equivalent; QE, quercetin equivalent; DPPH, 2,2-diphenyl-1-picrylhydrazyl; ORAC, oxygen radical absorbance capacity; CE, catechin equivalent; TE, trolox equivalent; PA, phenolic acid (mixture of gallic acid, protocatechuic acid, p-hydroxybenzoic acid, vanillic acid, p-coumaric acid, caffeic acid, ferulic acid, and chlorogenic acid); RE, rutin equivalent; FRAP, ferric reducing antioxidant power; ABTS, 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic) acid.

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