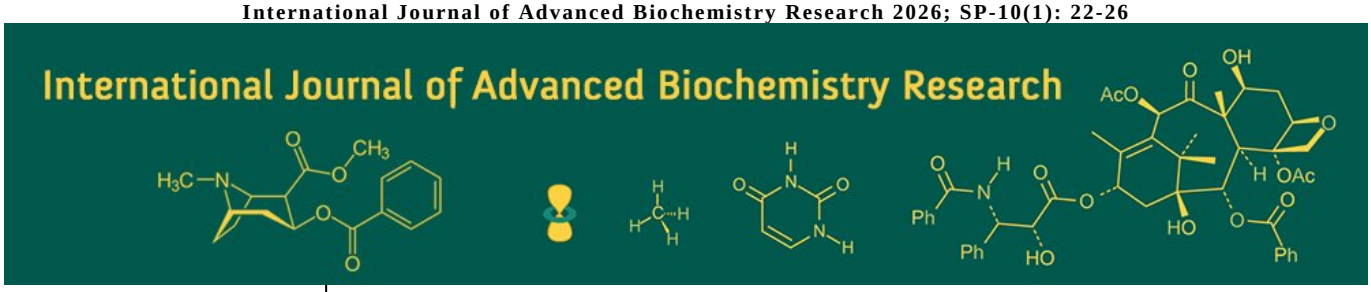

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Dr. Mukul Kumar
Department of Plant Physiology and Biochemistry, BAU, Sabour, Bihar, India

Dr. Akhilesh Kumar Singh
Department of Soil Science, BAU, Sabour, Bihar, India

Dr. Nawal Kishor Singh
Krishi Vigyan Kendra, ICAR-VPKAS Almora, Bageshwar, Uttarakhand, India

Neeraj Joshi
Krishi Vigyan Kendra, ICAR-VPKAS Almora, Bageshwar, Uttarakhand, India

Corresponding Author:
Dr. Nawal Kishor Singh
Krishi Vigyan Kendra, ICAR-VPKAS Almora, Bageshwar, Uttarakhand, India

Kaala Dhaan (Indian black rice) from heritage feasts to global exports: The genetics, phytochemical profiling, therapeutic applications, and modern commercial potential

Mukul Kumar, Akhilesh Kumar Singh, Nawal Kishor Singh and Neeraj Joshi

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Abstract
Traditionally revered as a heritage crop in the states of Manipur and Tamil Nadu, Indian black rice has recently been recognized as a vital functional food in the international market. Commonly referred to as *Chak-Hao* or *Karuppu Kavuni*, and distinct from Chinese black rice varieties, display rich nutraceutical values, predominantly containing anthocyanins, EAAs, and antioxidants This review includes contemporary research on black rice in terms of its botany, nutritional content, medicinal properties, and technological advancements, and with a special emphasis on export analysis and processing difficulties, thereby making *Kaala Dhaan* an integral contributor for overcoming hidden hunger and lifestyle illnesses.

Keywords: Kaala dhaan, indian black rice, therapeutic potential, pigmented rice, traditional ecological knowledge (TEK), value addition, health benefits

1. Introduction
The ancient China has a history of utilizing Black rice (*Oryza sativa* L.) before dynastic times (Newman, 2004) [18], often known by names like “emperor’s rice” or “forbidden rice,” it was valued/prized for its rarity and therefore served as a tribute food (Oikawa *et al.*, 2015) [19]. Contrary to Chinese varieties of Black rice (which were limited to aristocrats and royalty), Indian races like *Chak-Hao* (in Manipur) and *Karuppu Kavuni* (in Tamil Nadu) were historically integrated into community feasts and religious offerings (Devi *et al.*, 2024) [4]. In the current global market, Asia, specifically India, has appeared as a budding major market because of Indian black rice, also known as *Chak-Hao*, which has gained international recognition with its 2020 GI tag, thus ensuring economic returns with its easy availability on e-commerce platforms, and economic profits are reaching rural Indians because of this recognition, which has generated export interest in gourmet stores, making it a high-value functional food product (Devi *et al.*, 2024) [4]. The current business statistics from 2024 to 2025 report an annual growth rate of 23% in the export of Black Rice from India, directly competing with the existing production belts in China and Vietnam. Although China leads in the race to supply more volume, Indian variants are branded as 'Artisanal and Heritage Grains,' sold with high prices in the EU and US markets because of their better Aroma Uniqueness. Limited to the North Eastern Himalayas and scattered regions in Southern India earlier, the cultivation of 'Black Rice' is now experiencing an expansion strategy of 'Pan-India,' as of 2024, through the 'One-District One-Product' scheme, where experimental plantation activities were started in non-traditional growing states such as Maharashtra and Uttar Pradesh (VolzaTradeData,2025) [32].

1.1 Ethnobotany and Cultural Importance
The credit for survival of black rice in India must be given to tribal communities, who preserved the races by "Traditional Ecological Knowledge" (TEK). By them it was not merely grown for food, but also as a functional remedy (long before the term "nutraceutical" existed). Contrary to the present hight yielding "Green Revolution" varieties, these historical

races were grown and for centuries in rainfed conditions and with minimal external fertilizer inputs, and thereby making them reservoirs of stress-tolerant genes (Borah *et al.*, 2018) [1]. Two most prominent landraces of Indian Black Rice are:

a) Manipur (*Chak-Hao*): The name translates to "Delicious Rice" (*Chak* = Rice; *Ahaoba* = Delicious) in the Meitei language. Traditionally in Manipur, sisters present black rice to their brothers as symbol of love and prosperity during *Chak-Hao Amubi* ritual of the *Ningol Chakouba* festival. The brewed product, called *Chakhao-atingba* (Loukrakpam *et al.*, 2025) [14] is a a traditional beverage. Such socio-cultural importance was formally recognized with a Geographical Indication (GI) tag in 2020 by Government of India (GoI, 2020).

b) Tamil Nadu (*Karuppu Kavuni*): Known as "Burma Black" or the "Black Pearl," folklore suggests this variety was brought to Tamil Nadu from Burma by the Nattukottai Chettiars, a trading community who were once the primary financiers of Burma's rice industry (Rudner, 1994) [27].

2. Botany and Origin

Black rice differs from the normal white rice due to the deposition of anthocyanin pigments within the pericarp, seed coat, and aleurone layers (Goufo and Trindade, 2014) [8]. Black rice differs genetically from the wild ancestor *Oryza rufipogon*, which generally has red grains. Recent genomic studies indicate that the black trait originated through a mutation in the Kala4 gene on chromosome 4, a basic helix-loop-helix transcription factor. This rearrangement in the Kala4 promoter originally took place in the subspecies *tropical japonica* and then introgressed into the *indica* varieties through natural crossbreeding cross breeding (Oikawa *et al.*, 2015) [19]. This evolutionary distinctiveness categorizes Indian varieties such as *Chak-Hao and Karuppu Kavuni* as distinct landraces rather than mere hybrids.

3. Nutritional Profile and Phytochemistry

a) Macronutrient Composition

Indian black rice is being increasingly grouped with "functional foods." Proximate analysis shows that Indian black rice such as *Chak-Hao and Kalavati* has 8.5% to 9.0% protein content compared to 6.8% in white rice (Roy *et al.*, 2021) [26]. The protein part includes all nine essential amino acids with higher amounts of Lysine and Tryptophan than usually found in grains (Jha *et al.*, 2017; Javed *et al.*, 2025) [12, 11]. Moreover, it has lipids rich in lipophilic antioxidants such as gamma-oryzanol and tocopherols (Min *et al.*, 2011; Ito & Lacerda, 2019) [16, 10]. As mentioned by Miftahurrahmi *et al.*, 2025 [15] even if the fatty acid composition of black rice is primarily dominated by linoleic acid (same is case with white and red varieties) its functional lipid fraction is highly enriched.

b) Micronutrient Density

One of the strongest reasons for black rice being promoted as a food is its efficacy in fighting the problem of "Hidden Hunger." Variability in black rice was found to be high, along with higher mineral concentration. The iron content in black rice was found to be 3.5 mg/100g, while that of zinc was around 3.3 mg/100g (Kumari, 2020) [13]. Ramanathan *et al.* (2014) [22] directly compared the iron and calcium content in *Kavuni* black rice with improved white rice, finding that iron levels in black rice are 20-30% higher than in modern white rice, along with 33-45% higher calcium. It must be noted that iron & zinc in black rice could be unaffected by the amount of anthocyanin accumulation (Gogoi *et al.*, 2024) [7].

c) Phytochemistry: The Anthocyanin Advantage

The dark purple-black pericarp is determined by the *Kala4* gene. Cyanidin-3-glucoside (C3G) is the most abundant anthocyanin, followed by peonidin-3-glucoside, accounting for over 80% of total anthocyanin content (Thapa *et al.*, 2024; Zhang *et al.*, 2010) [30, 37]. HPLC analysis confirms the presence of both compounds (Sahewalla *et al.*, 2023) [28]. The total antioxidant capacity is notable, with phenolic content ranging from 37.101 to 493.611 mg GAE/100 g (Gallic Acid Equivalent per 100 grams). in studied genotypes.

d) Glycemic Index (GI) and GABA

Black rice, in particular the *Kavuni* variety, is characterized by possessing a low Glycemic Index (GI) food with a value of 53.10, attributed to its low simple starch (60%) and high resistant starch (38%) content. It also contained higher fibre content (4.7g/100g) (Parthiban, 2025) [20]. Moreover, upon germination, black rice exhibits a noticeable increase in Gamma-aminobutyric acid (GABA), a neurotransmitter aiding in stress reduction and hypertension management (Yamuangmorn *et al.*, 2024) [36].

4. Agronomy, Genetics, and Breeding

a) Genetics and Plant Breeding In the past, the constraints like low yield (<2.0 tonnes/ha) and lodging due to tall plant height were major bottlenecks. This changed for the better in 2024-2025, being a historic moment. The ICAR-Research Complex for NEH Region released *RC Manichakhao-1*, the first High-Yielding Variety (HYV) of black rice. This semi-dwarf crop has lodging resistance with an estimated yield potential of 4.5-5.0 tonnes/ha (PIB, GoI, 2024 pib.gov.in) [21]. In addition, Nameirakpam *et al.* (2024) [17] incorporated the blast resistance gene 'Pi54' with the high-yielding gene 'OsSPL14' using marker-assisted backcrossing in the Chak-Hao genome, resulting in line ChM 68 which retained high anthocyanin content (240.31 mg/100g).

b) Agronomy and Remote Sensing

Precision farming is increasingly being integrated into current agronomy practices. Rao *et al.* (2022) [23] employed Sentinel-2 satellite data along with the Modified Anthocyanin Reflectance Index (mARI) to differentiate black rice crops from green paddy fields. In efficient agricultural methods, Dambale *et al.*, (2025) [3] found that the application of vermicompost from the pseudo-stem of banana plants improved rice tillers and weight within the context of the System of Rice Intensification (SRI) method, providing an efficient alternative to the use of potash chemicals.

5. Clinical Biology and Therapeutic Mechanisms

Recent *in vivo* clinical trials provide evidence for health claims:

a) Malnutrition: In the groundbreaking study conducted by Sharma & Priyadarshini (2024) [29] at the Sambalpur

University, 'Nutri-Nest,' an iron-rich supplementary food prepared from Kalavati Rice (black rice race in Orrisa), reached conclusive weight gain and improvement from malnutrition when tested on mice pre-clin

b) Diabetes: Eviana *et al.* (2023) [5] demonstrated that the bioactive compound extracted from black rice bran, when given to Type 2 diabetic rats, increased insulin levels to almost normal, just like Metformin.

c) Healthy Ageing and Telomere Modulation: In trials done by Wattanathorn *et al.* 2025, proved that anthocyanin-containing rice formulation significantly increase healthy ageing. The supplementation changed telomere length, a key biomarker of cellular ageing, along with reduction systemic oxidative stress and inflammation. The work suggested that, black rice functions as a genomic modulator which is capable of mitigating age-related degeneration.

d) Cardiovascular Protection: in a six months trials conducted by Wang *et al.* (2007) [33] on 60 coronary heart disease (CHD) patients, results suggested that supplementation with Black Rice Pigment Fraction (BRF) noticeably improved plasma Total Antioxidant Capacity (TAC) and reduced critical inflammatory biomarkers (sVCAM-1 and hs-CRP). Thereby concluded that anthocyanins could play an active role in stabilizing atherosclerotic plaques and reducing vascular inflammation in patients.

e) Improvement in immunity and defence: Fan *et al.* in 2017 [6], demonstrated the immunomodulatory effects of black rice anthocyanins in WEHI-3 leukemia murine models. The extracts promoted in-vivo multiplication of T-cells (CD3) and macrophages (Mac-3) and augmented phagocytosis. Their work showed the potential of black rice in improving enhance immune surveillance in cases of immunocompromised subjects.

6. Value Addition and Processing Technology

Processing plays a key role in preserving the bioactivity of such products. According to Javed *et al.* (2025) [11], High-Temperature/Pressure Processing (HTP) at 115°C for 20 mins proved effective with increased heat-stable flavonoids and quercetin derivatives by 22%, whereas milling decreased anthocyanins by 74%, whereas in its application for the production of puff snacks, it preserved 70-80% of anthocyanins

Fermentation represents another area for value addition. In fact, the optimized procedures for Chak-Hao wine were assessed in a review undertaken by Loukrakpam *et al.* (2025) [14], which indicated that the fermentation process helps retain compounds like anthocyanins that act as a functional food competitor in the form of red wine in the foreign market due to its rich sensory attributes.

7. Global Economy and Market Dynamics

In 2024, the black rice market across the globe is calculated to be USD 9.38 billion, whereas at the end of the year, the figure is expected to reach USD 10.13 billion, with a CAGR of 8.5% (Research And Markets, 2025) [24-25]. Some major drivers are plant-based proteins and the natural colorant industry. This is a premium crop for Indian farmers. Comparing the Minimum Support Price for regular paddy rice at ₹23/kg, their organic black rice is sold for ₹80-120/kg in the domestic market (Introspective Market Research, 2025) [9]. Export markets are Europe, the USA, and New Zealand; but these strictly necessitate Organic Certification for the products when being exported. The most notable achievement was signing a MoU in 2025 for exporting Chak-Hao to Japan.

8. Major Challenges and Constraints

a) The Milling Paradox: Traditional milling machinery, calibrated for white rice, producing very low Head Rice Recovery (<50%) for black rice, leading to high breakage and value loss.

b) Cooking Time: Unpolished black rice takes 45-60 minutes to cook. Yet, innovations in 'Quick-Cooking' parboiled varieties are reducing this to below 20 minutes (Widyasaputra *et al.*, 2019; marketreportsworld.com, 2024) [35, 2].

c) Supply Chain: The 2023-2024 ethnic conflict in Manipur resulted in approx. 60% drop in exports, pointing to the danger of geographical centralization (The New Indian Express, 2024) [31].

d) Adulteration: There is an increased adulteration of white rice with artificially colored rice. More stringent FSSAI regulations are required to cope with this menace, along with consumer awareness through domestic tests (simple water tests).

Table 1: Key Scientific Advancements in Therapeutic Potential, Agronomy, and Processing of Indian Black Rice

S No	Category	Key Finding	Outcome / Data	Reference
1	Healthy Ageing	Telomere Modulation	Anthocyanin-enriched formulation modulated telomere length and reduced oxidative stress in geriatric trials, acting as a genomic modulator.	Wattanathorn *et al.* (2025) [34]
2	Cardiovascular	Plaque Stabilization	Supplementation with Black Rice Pigment Fraction (BRF) improved plasma antioxidant capacity and reduced inflammatory markers (sVCAM-1, hs-CRP) in CHD patients.	Wang *et al.* (2007) [33]
3	Diabetes	Insulin Regulation	Bioactive compounds from black rice bran restored insulin levels in Type 2 diabetic rats to near-normal levels, comparable to Metformin.	Eviana *et al.* (2023) [5]
4	Immunity	Immunomodulation	Extracts significantly enhanced *in vivo* proliferation of T-cells and macrophages, improving immune surveillance in leukemia models.	Fan *et al.* (2017) [6]
5	Nutrition	Malnutrition Recovery	Nutri-Nest' supplementary food resulted in conclusive weight gain and recovery from malnutrition in murine models.	Sharma & Priyadarshini (2024) [29]
6	Agronomy	First HYV Release	Release of RC Manichakhao-1, a semi-dwarf, lodging-resistant variety with a yield potential of 4.5-5.0 t/ha (vs. traditional <2.0 t/ha).	PIB. GoI, 2024 pib.gov.in, [21]
7	Breeding	Marker-Assisted Selection	Developed line ChM 68 by incorporating blast resistance (Pi54) and high-yield (OsSPL14) genes while retaining high anthocyanin (240 mg/100g).	Nameirakpam *et al.* (2024) [17]
8	Processing	Nutrient Retention	High-Temperature/Pressure (HTP) processing (115 °C) increased heat-stable flavonoids by 22%, whereas traditional milling destroyed 74% of anthocyanins.	Javed *et al.* (2025) [11]
9	Value Addition	Fermentation	Optimized fermentation (wine) retains anthocyanins and offers sensory attributes competitive with premium red wines.	Loukrakpam *et al.* (2025) [14]

9. Conclusion and Future Prospects

Indian Black Rice, Kaala Dhaan, occupies the space where traditional agricultural practices meet the nutraceutical food system. The product's history, which ranges from the royal cuisines of Manipur to the health food shelves in the West, establishes its robustness. For future success, its cultivation needs to be decentralized to non-traditional states to deal with potential supply chain issues, technological advancements for low-cost processing methods should be pursued for small farmers, and then from animal-based studies to human clinical studies should be pursued to establish its health properties. The black rice crop is not just an agricultural product; it is an opportunity for the bio-fortification of nutritional deficiencies with the global demand for organics.

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