



## Review article

# Regenerative rice farming for sustaining productivity, reducing energy demand, and methane emissions in India: A comprehensive review



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## ABSTRACT

Rice is cultivated on approximately 165 million hectares in over 100 countries, serving as a staple food for >3 billion people. Asia accounts for ~90% of global rice production, while rice contributes around 40% of India's food grain production. Traditional rice cultivation relies heavily on water resources (between 1000 and 2000 mm), consumes high labour and energy, and emits substantial amounts of methane gases. As estimated, the annual mean atmospheric concentration of methane (CH<sub>4</sub>) ranged from 1889 to 2017 ppb (2020 annual mean across India), which is critical and demands an alternative, sustainable solution. Thus, the regenerative rice system stands out as a viable option to address these environmental challenges and can contribute to sustainable agricultural development while also reducing energy demands. This method employs direct seeding in non-puddled fields. It creates an aerobic soil environment, promoting strong rice roots and a median water reduction of 52.5% (IQR: 45–60%;  $n = 16$  studies), thriving on 600–700 mm. Similarly, based on field experiments, an average decrease in energy consumption of 24.5% (IQR: 6.4–42.5%;  $n = 9$  studies) and a 56% reduction in methane emissions (IQR: 34–78%;  $n = 9$  studies) were observed. Regenerative rice contributes to Sustainable Development Goals 2 (Zero Hunger), 12 (Responsible Production and Consumption), 13 (Climate Action), and 15 (Life on Land), while reducing environmental impact compared to a puddled rice system. To evaluate its potential for scaling, this review examines existing research on regenerative rice production systems and proposes directions for future research, extension, and policy advocacy.

## 1. Introduction

Rice, scientifically known as *Oryza sativa* L., is one of the world's primary staple food crops, feeding a population of more than 3 billion,

providing sustenance, ensuring food security, and contributing to rural livelihoods. The rice crop is widely cultivated on 165.04 million hectares of land covering 100 countries across the globe [1]. Asia produces and consumes approximately 90 % of the rice produced worldwide, which

**Abbreviation:** AWD, Alternate wetting and drying; AWG, Alternating wet and dry; B, Boron; Ca, Calcium; CH<sub>4</sub>, Methane; CO<sub>2</sub>, Carbon dioxide; DAS, Days after sowing; DS, Direct seeding rice; EC, Electrical conductivity; Eh, Redox potential; ET, Evapotranspiration; FC, Field capacity; Fe, Iron; FDF, Flooding drainage flooding; FYM, Farmyard manure; GDD, Growing degree days; GEE, Google Earth Engine; GHG, Greenhouse gases; GWP, Global warming potential; H, Sensible heat flux; ha, Hectare; IPCC, Intergovernmental panel on climate change; K, Potassium; Kc, Crop coefficient; LE, Latent heat flux; LER, Land equivalent ratio; LCC, Leaf color chart; Mg, Magnesium; MI, Moist irrigation; Mn, Manganese; N, Nitrogen; N<sub>2</sub>, Dinitrogen; N<sub>2</sub>O, Nitrous oxide; NH<sub>4</sub><sup>+</sup>, Ammonium; NIR, Near-infrared; NO<sub>2</sub>, Nitrogen dioxide; NO<sub>3</sub><sup>-</sup>, Nitrate; P, Phosphorus; PCU, Polymer-coated urea; ppb, Parts per billion; RA, Regenerative agriculture; RCBD, Randomized complete block design; RF, Rainfed; RR, Regenerative rice; RUE, Resource use efficiency; S, Saturation point; Si, Silicon; SMP, Soil moisture potential; SO<sub>4</sub><sup>2-</sup>, Sulfate; SRI, System of Rice Intensification; SSC, Saturated soil culture; SSNM, Site-specific nutrition management; STCR, Soil test crop response; WUE, Water use efficiency; WPET, Crop water productivity.

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can supply up to  $\frac{3}{4}$ <sup>th</sup> of the calories required by 520 million people in Asia [2]. Approximately 90 % of all freshwater in Asia is used for crop irrigation, with 50 % allocated specifically to rice cultivation [3]. Traditional puddled rice (TPR) cultivation, which relies heavily on water availability and inundation, is particularly vulnerable in the face of water scarcity and unpredictable rainfall. In India, irrigated rice is cultivated on around 59% of the country's total rice land area. The production and productivity of milled rice in India are 177.65 million tons and 2.89 tons per hectare, respectively [4]. Rice in India is grown predominantly by the conventional transplanting method (land preparation with standing water in the field) [5]. This traditional method of rice cultivation is water-intensive. Hence, the decrease in irrigation water availability demands a sustainable and improved method of rice cultivation [6]. However, the availability of fresh water is diminishing throughout Southeast Asia due to several human-induced problems [7]. Furthermore, it is projected that a physical water shortage will affect 15 million hectares of irrigated rice fields by 2025, while 22 million hectares of South and Southeast Asian dry-season rice will experience economic water scarcity [8]. This has significant implications for resource-poor smallholder farmers in India. Rice is a staple crop in India, deeply embedded in the country's cultural, social, and economic fabric. It sustains millions, ensuring food security and contributing to rural livelihoods. However, traditional methods of Puddled rice cultivation, practiced for centuries in India, face significant challenges in a changing climate.

Climate change poses threats to agricultural systems worldwide, including rice cultivation [9,10]. The dynamics of rice production are changing due to the intensified frequency of extreme events, irregular precipitation patterns, and elevated temperatures. At the same time, about 25 % of total anthropogenic greenhouse gas (GHG) emissions are produced from agriculture and land-use change, which is a major source of GHG ([11–14]a). Traditional rice farming practices, owing to puddled/submerged conditions, degrade the environment by releasing enormous amounts of GHGs, such as carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), and particularly methane (CH<sub>4</sub>). These practices require a huge volume of irrigation water and labor for transplanting and field maintenance [15]. Therefore, such a traditional rice transplanting method is well-suited in high rainfall regions and low labor costs. Apart from that, the traditional rice production system is an energy-, fertilizer-, and capital-exhaustive practice [16]. The increasing intensity of puddling leads to a reduction in bulk density [17] and a decreasing trend in aggregate stability [18] and macropores [19]. However, in India, the agricultural labor shortage has become chronic, as employment opportunities in nearby urban centers are increasing, leading to migration and increased cost of production (with mechanization). As a result, farmers in India face labor scarcity for agricultural operations [20]. Moreover, approximately 60 percent of Indian farmers are small to medium landholders, unable to afford large machinery to overcome labor shortages [21,22]. Rice productivity and production in India need to be sustainably increased to meet the demands of an increasingly populous country. This increase needs to be achieved with limited resources such as water [21] and labor. To address these challenges, innovative and sustainable agricultural practices such as regenerative rice cultivation are gaining recognition and acceptance at the landscape level [23].

Regenerative rice is a novel concept utilizing ecosystem regeneration techniques and nature-first soil practices to mitigate greenhouse gas emissions, cut back on chemical inputs, conserve water, and boost yields. Regenerative rice focuses on aerobic or direct-seeded rice cultivation using non-puddled and non-saturated soil. Aerobic rice is primarily grown under aerobic soil conditions throughout its life cycle (like the cultivation practice of pulses). In contrast, in direct-seeded rice, seeds are sown (drilled) directly into the field as opposed to the more conventional approach of raising seedlings in nurseries before transferring them into the fields. Regenerative rice minimizes soil disturbance and water use. It enables intercropping/sequence cropping for system intensification and boosts resource use efficiency. These traits

address climate change, water scarcity, methane emissions, and soil health. Compared to traditional irrigated systems, this system, including varietal selection and crop management, uses substantially less water and yields 4.5–6.5 t ha<sup>-1</sup> [24–26]. In India, where rice production is extensively practiced and essential for food security, implementing sustainable methods such as regenerative rice production becomes crucial. This review article focuses on a regenerative rice production system that combines aerobic and direct-seeded rice to raise awareness among readers and stakeholders about its innovative concept. In the Indian context, regenerative rice cultivation is a sustainable practice that has been extensively examined in this review paper. It explores the potential of regenerative rice in mitigating the challenges posed by climate change, focusing on water conservation, reducing methane emissions, lowering energy consumption, and improving soil health.

This study fills research gaps and examines the advantages and challenges of regenerative rice systems by synthesizing the existing body of knowledge. Direct-seeded rice, alternate wetting and drying, and rice intensification systems are some of the examples of regenerative rice system techniques designed to enhance soil health, conserve water, and promote sustainable agriculture. Farmer productivity can be maintained while their environmental impact is decreased by implementing regenerative practices. Overall, this comprehensive analysis examines the potential adaptability of regenerative rice cultivation in India, investigating its compatibility with diverse soil compositions and prevailing climatic conditions. Highlighting the challenges associated with traditionally transplanted puddled rice methods, the study emphasizes the transformative benefits of transitioning to regenerative rice cultivation, ensuring food security and environmental sustainability. Furthermore, it delves into the intricacies of energy-efficient agronomic practices tailored for regenerative rice cultivation, accompanied by pertinent policy recommendations to facilitate their widespread adoption.

## 2. Methodology

### 2.1. Literature research

An extensive literature search gathered studies on regenerative rice cultivation from peer-reviewed publications. We searched Google Scholar, Web of Science, and Scopus using keywords: 'regenerative rice,' 'direct-seeded rice,' 'methane emissions,' 'GHG,' 'water savings,' and 'energy use' in puddled vs. regenerative rice. Only original studies on aerobic rice and transplanted rice that involved both field and greenhouse experiments were included; studies based on computer modeling or simulations of aerobic rice were excluded. Reviewed articles, research papers, and reports published on aerobic rice within the past decades are included to ensure up-to-date information. A total of 153 publications on aerobic rice and transplanted puddled rice are included in this review. The national database on aerobic rice can benefit from the data in this review. The results of several studies will inform the development of effective policies for farmers engaged in agriculture. This study implements the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol [27,28] to review the published information related to regenerative and puddled rice cultivation.

This review paper is structured into different sections, and these are as follows: The first section is "Adaptability of Regenerative rice in India"; in this, we summarized the studies related to climate, soil, and varieties of aerobic/direct-seeded rice in the Indian context. The second section is "Regenerative rice crop management". In this section, research articles on different crop management practices (such as preparatory cultivation and sowing, water management in regenerative rice in comparison to transplanted puddled rice cultivation, intercropping, nutrient management, weed management, disease, and insect pests' management) related to regenerative rice taking Karnataka as a case study along with other researchers' outcomes, are supported and presented. The next section, "Climate change and rice cultivation," summarizes the role of traditional rice cultivation practices in contributing

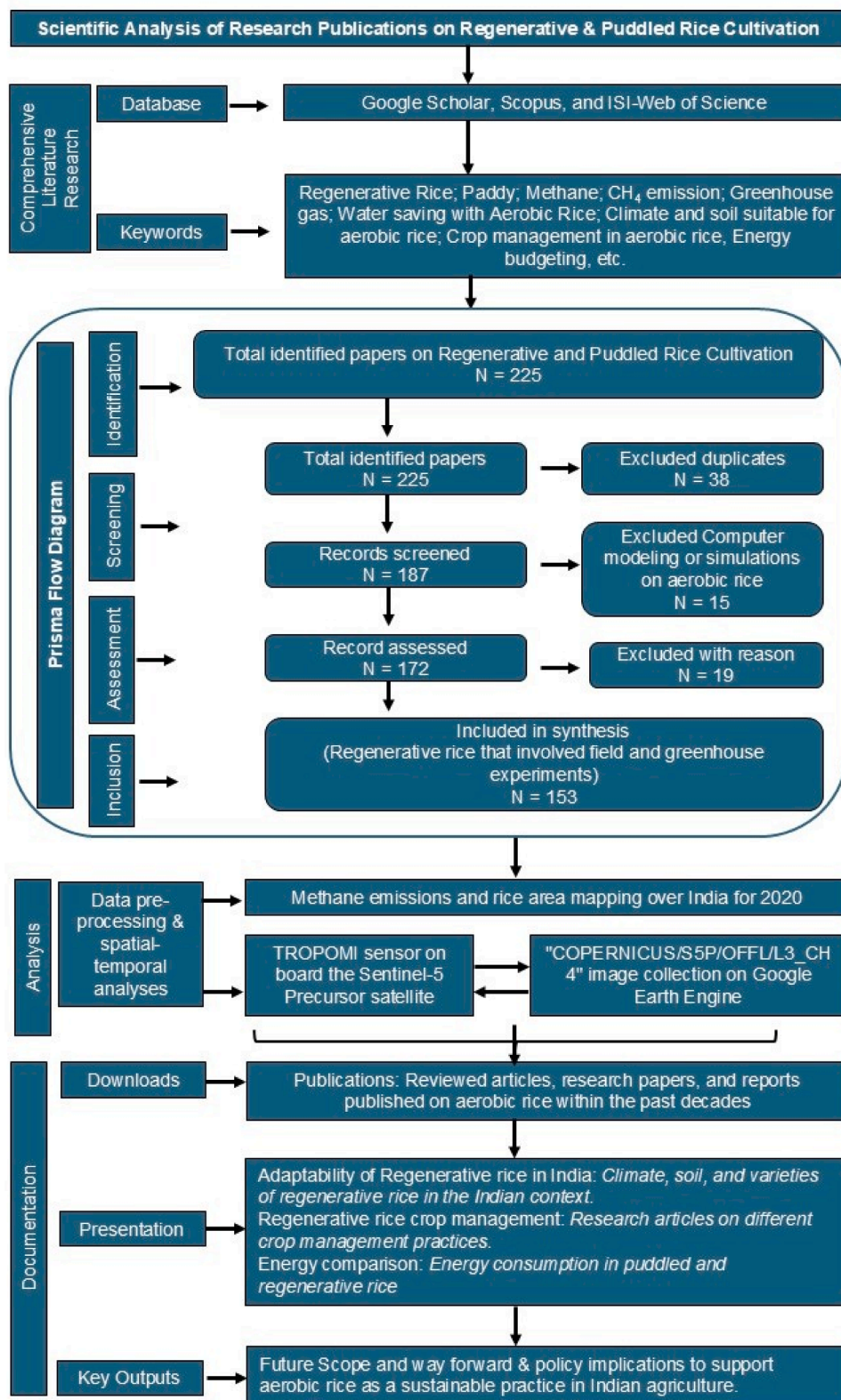


Fig. 1. Flow chart showing the bibliographic analysis.

to climate change by increasing greenhouse gas (GHG) emissions, specifically methane. Afterward, a section, "Energy consumption rates in transplanted puddled rice and regenerative rice system," describes how regenerative rice practices help reduce energy consumption rates by minimizing the fuel, labor, fertilizer, electricity, etc., compared to

puddled transplanted rice. Finally, in the "Conclusions and Way Forward" section the significant findings of this review and key areas of future research on regenerative rice are summarized. A detailed framework of the article has been illustrated in Fig. 1.

**Table 1**

Soil organic matter and nutrient availability under transplanted puddled rice and regenerative rice system.

| Parameter                  | Transplanted Puddled Rice   | Regenerative Rice System   |
|----------------------------|---|--|
| pH                         | Will become neutral   | Ambient pH   |
| Organic                    | Increases in C and N accumulation   | Rapid decomposition and accumulation of relatively slow carbon dioxide (CO <sub>2</sub> )                                      |
| Carbon                     | Organic acids, alcohols (reduced forms of C)  |  |
| C:N ratio                  | Greater C:N ratio as a result of organic C  | Varies with soil and organic matter management   |
| Methane (CH <sub>4</sub> ) | High production (aerobic decomposition)   | Minimal production   |
| NH <sub>4</sub> -N         | Production and accumulation favored (NH <sub>4</sub> <sup>+</sup> reduced)  | Oxidized to nitrate, which is susceptible to loss through denitrification and leaching (NO <sub>3</sub> <sup>-</sup> oxidized) |
| P                          | P availability increased Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> , precipitation  | PO <sub>4</sub> <sup>3-</sup> (stable in both conditions)  |
| K                          | Increased K availability  | Not applicable   |
| S                          | S availability reduced due to Sulfide (S <sub>2</sub> <sup>-</sup> ) formation  | Availability is normal due to oxidized sulfate (SO <sub>4</sub> <sup>2-</sup> )  |
| Fe                         | Increased availability of Fe in alkali and calcareous soils; Toxicity in acidic soils due to excess reducible iron (Fe <sub>2</sub> <sup>+</sup> ) concentrations | Fe deficiency in calcareous and high-pH soils (Fe <sup>3+</sup> more soluble)  |
| Mn                         | Reduced solubility (Mn <sup>2+</sup> reduced, more soluble)   | Toxicity in acid soils based on pH (Mn <sup>4+</sup> /Mn <sup>3+</sup> oxidized, less soluble)                                 |
| Cu, Zn, Mo                 | Increased availability of Cu and Mo, but not of Zn  | Depends on soil pH   |
| Al                         | No Serious problem  | Serious problem in acidic soils  |
| Reduction products         | Sulfide and organic acids produced may be toxic   | Not a problem  |

Source: Adapted from [40].

## 2.2. Estimation of methane levels in the atmosphere using remote sensing

In this study, we analyzed data of the Sentinel-5P satellite to examine atmospheric methane concentrations across India. We focused on the column-averaged dry-air mixing ratio of methane, expressed in parts per billion (ppb), for the period spanning from January 2020 to December 2020. Specifically, we utilized imagery obtained from the Tropospheric Monitoring Instrument (TROPOMI) sensor on board the Sentinel-5 Precursor satellite, which follows a polar sun-synchronous orbit and passes over the study area at approximately 13:30 local time. The TROPOMI instrument provides constant sensitivity to the Earth's surface by observing methane columns through solar backscatter in the 2.3  $\mu\text{m}$  absorption region, providing high sensitivity to surface and boundary-layer methane under clear-sky conditions [29,30]. To acquire the necessary datasets, we accessed the "COPERNICUS/S5P/OFFL/L3\_CH4" image collection on Google Earth Engine (GEE), which provides Level-3 gridded CH<sub>4</sub> products derived from the operational offline (OFFL) retrieval pipeline. The datasets comprise georeferenced raster files in GeoTIFF format with a spatial resolution of 7  $\times$  7 km ([31]). To ensure data quality, we implemented a quality assurance (QA) filter that retains only pixels with a qa value  $\geq 0.5$ , in accordance with the recommendations of the Copernicus Sentinel-5P product user guide and prior validation research studies [30,32]. Previous global and regional validations indicate that TROPOMI XCH<sub>4</sub> retrievals generally display minimal residual biases within  $\pm 1\%$  (approximately  $\pm 10$  ppb), with mean biases across Asia +5 to +8 ppb in comparison to TCCON and GOSAT observations [32,33], confirming the robustness of the Level-3 product for large-scale analysis. The daily data were aggregated to monthly and annual means (for 2020) by arithmetic averaging within GEE. Ocean pixels and areas with consistent cloud cover were masked to minimize spurious retrievals. Although TROPOMI offers improved global coverage relative to earlier sensors, its sensitivity to near surface

methane concentrations is constrained, as retrievals are affected by the vertical sensitivity of the averaging kernel, which tends to highlight mid and upper-tropospheric layers [32,34]. Thus, the spatial CH<sub>4</sub> patterns identified represent column-integrated enhancement rather than direct emission fluxes. Note that these TROPOMI-derived atmospheric CH<sub>4</sub> concentrations (1889–2017 ppb annual mean in 2020) illustrate spatial patterns over India but do not quantify field-level emission fluxes; the reported 34–78 % methane reduction range in regenerative rice systems exclusively from comparative field experiments (e.g., direct-seeded vs. puddled systems), as synthesized in subsequent sections. In this study, we used the MOD13Q1.6 product, which provides a 16-day time series at 250 m spatial resolution for mapping different rice ecologies in India. The MOD13Q1 product contains several vegetation indices, including blue, red, near-infrared (NIR), and mid-infrared bands. Twelve tiles were obtained from the Land Processes Distributed Active Archive Center (LP DAAC) at <https://lpdaac.usgs.gov> to explore the South Asian region [35]. The Modis Reprojection Tool (MRT) was used to re-project and combine the twelve tiles into a single composite (Gumma et al. [36, 37].

## 3. Results and discussion

### 3.1. Adaptability of regenerative rice to climate, soils, and varieties

Regenerative rice offers an alternative approach that can be practiced in regions facing water scarcity or erratic rainfall patterns. Recent advancements have led to the development of high-yielding and drought-tolerant regenerative rice cultivars. A new production method, known as the regenerative rice system, grows rice in non-puddled and non-saturated soil. The projected yields in this system are double or triple compared to those obtained under upland conditions but slightly lower than those obtained under lowland puddled conditions. This rice system has, nevertheless, proven effective in cool temperate climates [38].

Rice production is successfully possible through efficient water and soil fertility management [39]. Rice is a subaquatic plant, and due to the presence of aerenchyma cells in its roots, it is well-adapted to puddled soils. Therefore, derives the advantages that come with flooding of the soil [40]. The pH and redox potential (Eh) of the soil, which determine its fertility and availability of nutrients, are strongly influenced by flooding [41]. The availability of ammonium (NH<sub>4</sub><sup>+</sup>), calcium (Ca), nitrogen (N), magnesium (Mg), phosphorus (P), iron (Fe), potassium (K), manganese (Mg), and silicon (Si) is increased when soil is submerged in water. This process tends to stabilize the pH in the neutral (6.5–7.5) range (Table 1). Sulphur (S) availability is reduced due to sulfate reduction into sulfide. A reduction in oxidation–reduction or redox potential in submerged or puddled conditions increases the Fe and manganese (Mn) contents due to the reduction of Fe<sub>3</sub><sup>+</sup> to Fe<sub>2</sub><sup>+</sup> and Mn<sub>4</sub><sup>+</sup> to Mn<sub>2</sub><sup>+</sup>, which are the primary changes that occur in Puddled or water-logged rice soils. Flooding caused alkaline soil to lose pH and acidic soil to gain pH. Additional findings include the following: nitrate (NO<sub>3</sub><sup>-</sup>) and nitrogen dioxide (NO<sub>2</sub>) are reduced to dinitrogen (N<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O); carbon dioxide (CO<sub>2</sub>) is reduced to methane (CH<sub>4</sub>); sulfate (SO<sub>4</sub><sup>2-</sup>) is reduced to sulfide (S<sub>2</sub><sup>-</sup>); phosphorus, calcium, magnesium, iron, manganese, molybdenum, and silicon are improved in concentration and availability; and zinc, copper, and sulfur are decreased in concentration and availability. The influence of the adoption of regenerative rice on the soil environment and its co-benefits has been illustrated in Fig. 2.

The rice crop is grown in diverse soil types, varying widely from acidic to alkaline conditions. Therefore, in the current scenario where regenerative rice is becoming inevitable, simple solutions could involve delineating regions with a standard pH range (6–8) and salt contents that can be easily converted to regenerative rice. In regions with problematic soils, recommended amelioration measures must be adopted before transitioning to regenerative rice practices. For instance, from the

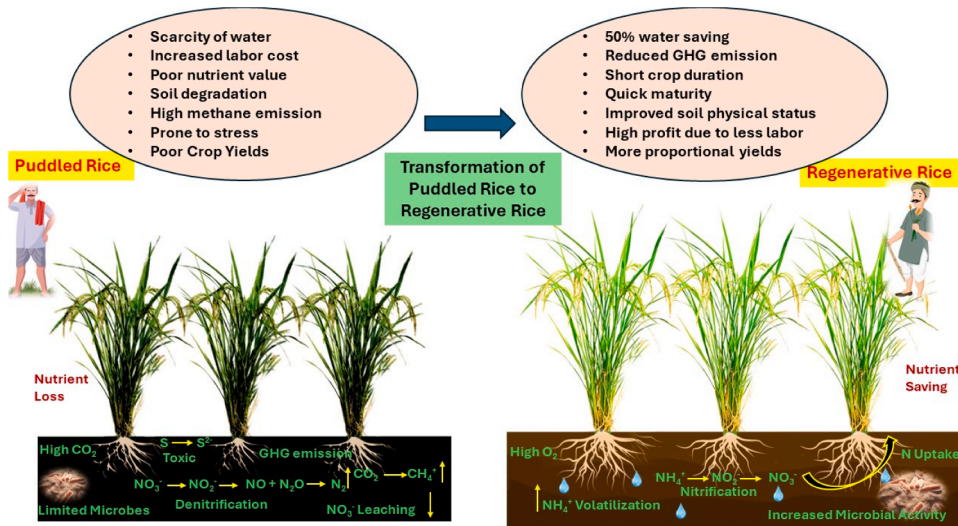


Fig. 2. Ecological benefits of transforming transplanted puddled rice into regenerative rice system.

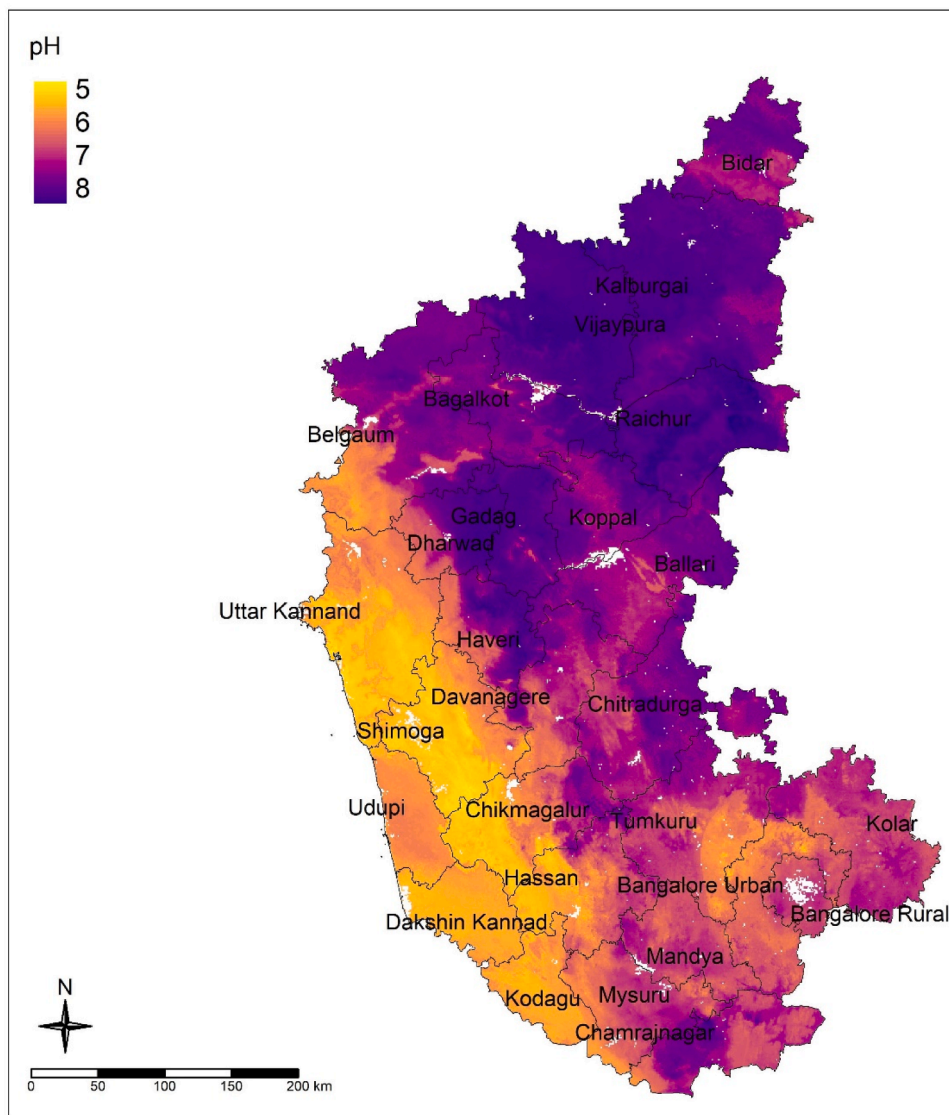


Fig. 3. Spatial distribution of pH of surface soil of Karnataka state.

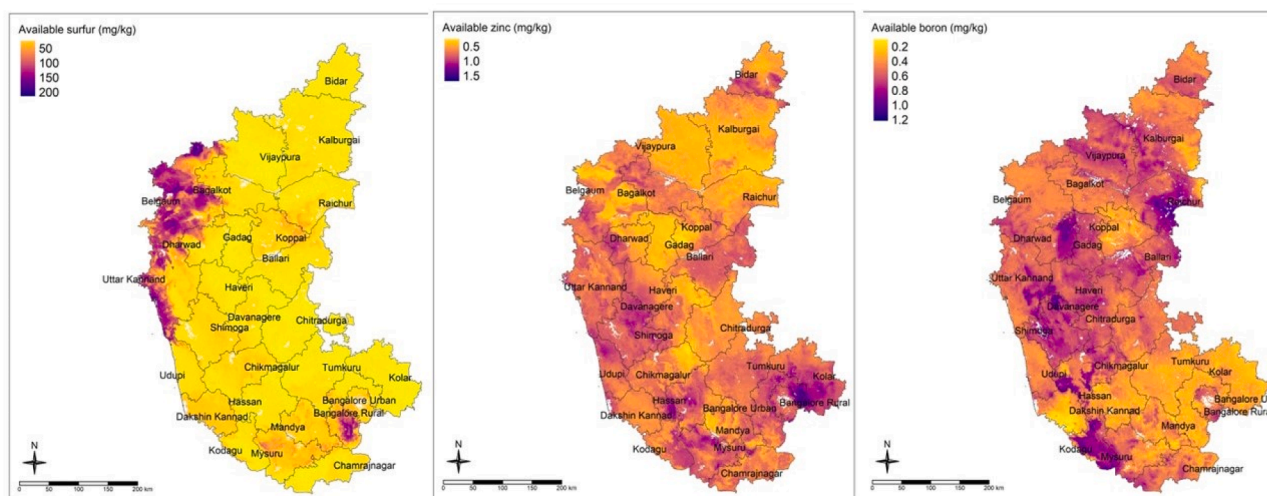


Fig. 4. The variation in available Sulphur, Zinc, and Boron in the soils of Karnataka.

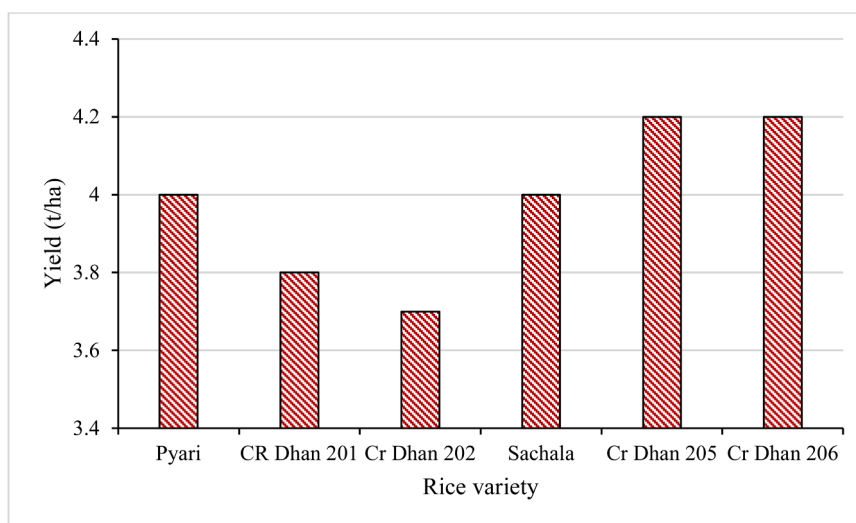


Fig. 5. Rice varieties developed by ICAR-NRRI, Cuttack suitable for aerobic/regenerative rice cultivation [54].

pH and EC perspectives, Karnataka soils [40] can be easily classified as regenerative rice soils (Fig. 3). Soil physical properties, particularly soil structure, assume a more critical role under arable than puddled conditions [42].

The role of organic matter in enhancing soil structure is well documented. Therefore, the organic fertilizer inputs under regenerative conditions should be focused on for improved plant growth and yields. Moreover, detailed soil health mapping of Karnataka [40] revealed that soils are sufficient in available K, Fe, and Cu, offering an opportunity to switch to regenerative rice cultivation from flooding practices. Widespread nitrogen (N) and phosphorus (P) deficiencies are found in Karnataka; thus, puddled rice cultivation has an advantage in ensuring nutrient availability, whereas regenerative rice cultivation requires agronomic support to ensure N and P nutrition. As S and Zn deficiencies are recorded in most farmers' fields, they need to be supplemented in both regenerative and puddled rice cultivation (Fig. 4). The implication of soil organic matter under regenerative conditions may also negatively affect the availability of boron (B), which is influenced by soil organic matter [43,44]. Therefore, B needs to be included in fertilizer management practices for regenerative rice. Regarding water input, studies indicate that rice can be grown successfully under low water conditions without affecting yields [45]. However, the benefits arising out of

flooding need to be captured. Therefore, to grow rice under certain circumstances, a strategy that incorporates the creation of rice cultivars and the integration of soil, water, and nutrient management approaches as a technology package is needed [42,46–48].

Aerobic rice cultivars are broadly considered input-responsive rice varieties with aerobic adaptation. These are grown by direct seeding in unpuddled and unsaturated soils [49]. Thus, rice cultivars that combine the drought tolerance of upland rice with the high-yielding properties of lowland varieties are necessary to produce large yields in regenerative soil conditions [50,51]. Due to their robust root systems, plant vigor, and plant stand, they can withstand brief water stress during both the vegetative and reproductive stages. The day to maturity is 115 to 120, yielding 5.5 tonnes of grain and 6 tonnes of fodder per hectare [52]. On the other hand, conventional upland rice cultivars, tailored to low-input systems, and aerobic rice varieties possess characteristics similar to those of lowland high-yield types, with adaptation to aerobic soils. To address water scarcity issues that are likely to worsen in the near future, regenerative rice systems using drought-tolerant varieties is recommended. These varieties have previously been tested in sub-optimal settings in India [53]. Fig. 5

A few aerobic rice varieties developed by the University of Agricultural Sciences (UAS), Bangalore (MAS 946–1; MAS 26, and MAS 868)

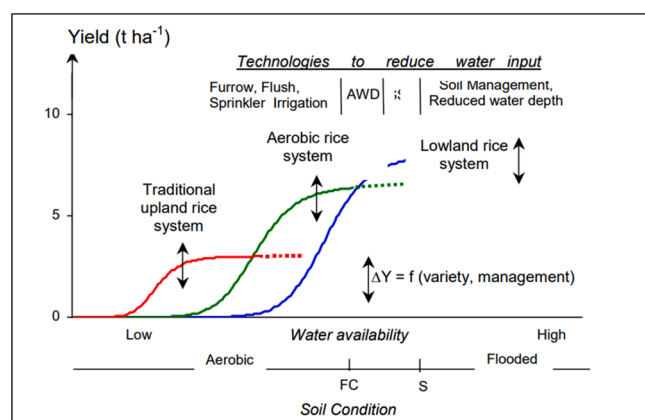


Fig. 6. Water Use Efficiency in Various Rice Cultivation Technologies.  $\Delta Y$  = change in yield, FC = field capacity, AWD = alternate wetting and drying, S = saturation point, SSC = saturated soil culture. (Source: [68]).

are now available for aerobic cultivation in India [55]. The marker-assisted selection tool was used to breed and release MAS 946-1 and MAS 26 for the South-Eastern Dry Zone of Karnataka in 2007 and 2008, respectively [52]. The varieties suitable for aerobic situations, viz, MAS 946-1, have higher root traits and yield components [56] and perform better than the existing check variety. For instance, the Rasi variety at all the locations of the Southeastern dry zone of Karnataka has an average grain yield advantage of 24.91 percent [56]. Farmers in the Bangalore Urban, Bangalore Rural, Kolar, and Tumkur districts of Karnataka's Southeastern Dry Zone (Zone-5) were persuaded to practice aerobic rice growing and embraced the novel rice variety MAS 946-1 [52]. Similarly, researchers identified some promising varieties with high-yielding traits for aerobic cultivation, viz, Doddabyranellu [55], MAS26, 25P25, SEL 128, MAS946-1, MAS25, IR 58025B, and PHB 71 [56]. Budha and IR64 were crossed to create the cultivar BI 33 (ARB6), a high-yielding rice variety with aerobic adaptations, at the UAS, GKVK, Bangalore. Due to its deep roots, which can draw moisture from the soil column's deeper layers, it has demonstrated a high degree of drought resilience [57]. It produces a high yield equivalent to that of improved varieties when there is sufficient moisture.

### 3.2. Practices for enhancing regenerative rice performance

#### 3.2.1. Land preparation

Land preparation in regenerative/aerobic rice cultivation involves plowing the ground twice or thrice with a tractor-drawn cultivator at optimum soil moisture conditions [58]. After tilling, a tractor or bullock-drawn tool (such as a blade harrow) is used to harrow the ground to create a level seedbed for planting. Thus, water can be conserved through aerobic practices by avoiding wetland preparation, which involves soil soaking, plowing, flooding, and puddling that consume large quantities of water and energy [59]. For tillage, minimum tillage has shown promising results under aerobic rice cultivation. However, aerobic rice has some limitations under completely zero-tilled conditions [60]. A study on aerobic rice time of seeding in Karnataka revealed that the grain yield of aerobic rice sown early, i.e., at the onset of the monsoon period (viz, between 30th May and 15th June), was higher than the late sown situation [61]. It was discovered that using a lower seed rate (5 kg ha<sup>-1</sup>) and a wider spacing between seeds (25–30 cm) was ideal for the aerobic method of rice establishment [61]. When compared to other spacing, aerobic rice planted with a 30 × 40 cm spacing reported significantly greater panicle length, plant height, number of seeds per panicle, hundred seed weight, and number of tillers per hill; however, a 30 × 15 cm spacing resulted in significantly higher seed production [62]. As a result, this study implies that to increase the yield of regenerative rice, it is crucial to sow it at the right time and with

Table 2

Recommended management practices for optimal regenerative rice production in Karnataka.

| Location         | Recommended management practices   |
|------------------|--|
| <b>A.</b>        | <b>Land preparation and spacing</b>  |
| <b>Bangalore</b> | Well ploughed, fine-tilled soil fertilized with decomposed organic matter/ green leaf manure is recommended ( <a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a> )<br>2. 30 cm x 12 to 15 cm is recommended ( <a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a> ) with one seedling hill <sup>-1</sup> . However, 45 cm × 20 cm spacing was also reported for optimum yield [55]  |
| <b>Shimoga</b>   | • 30 cm × 30 cm is recommended [82].   |
| <b>Mandya</b>    | • 30 cm × 40 cm found good in enhancing growth attributes whereas for obtaining higher yield, 30 cm × 15 cm spacing is recommended [62].   |
| <b>B.</b>        | <b>Nutrient management</b>   |
| <b>Bangalore</b> | • 100:50:50:30 NPK and Zn + FYM 10 t ha <sup>-1</sup> + Biofertilizers (soil application of <i>Azospirillum</i> and PSB ( <i>Bacillus megaterium</i> ) 4 kg ha <sup>-1</sup> each mixed with 8 kg of FYM) + IWM practice (Pyrazosulfuron @ 25 g ha <sup>-1</sup> pre emergence + HW @ 20 DAS) is recommended for higher yield [83] and maximum uptake of nutrients by aerobic rice [84].<br>• As regards split application, a basal dose of NPK @ 50:50:50 kg ha <sup>-1</sup> must be applied at sowing, and the remaining 50 kg N ha <sup>-1</sup> should be applied at the peak vegetative stage (45 DAS). Spray of foliar silicon is also recommended ( <a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a> )<br>4. 50 kg ha <sup>-1</sup> of P <sub>2</sub> O <sub>5</sub> and K <sub>2</sub> O + Leaf Colour Chart (LCC) based N application of 75 kg N ha <sup>-1</sup> (three splits of 15 kg N ha <sup>-1</sup> each time) + calcium silicate at 2 t ha <sup>-1</sup> is recommended <sup>a31</sup> |
| <b>Shimoga</b>   | • 50 % RDN through I fertilizers + 50 % RDN through vermicompost (spacing of 30 cm × 30 cm) recorded higher plant growth attributes [85].<br>• Soil application of zinc and iron recorded significantly higher grain yield as compared to other methods [82].  |
| <b>Mandya</b>    | • Researchers found fertilizer dose ranging from 100:50:50 kg NPK [83] along with 10 ton of FYM ha <sup>-1</sup> to 125:62.5:62.5 kg NPK (optimum for obtaining higher net returns as well as benefit cost ratio (2.7)).<br>• Higher total dry matter at harvest and higher NPK uptake (124.2, 30.6 and 93.9 kg ha <sup>-1</sup> , respectively) recorded with recommended dose of fertilizer [86] (100:50:50 kg N: P: K ha <sup>-1</sup> ) + 10 tons of FYM ha <sup>-1</sup> .<br>• Application of fertilizer at the rate of 125:62.5:62.5 kg NPK ha <sup>-1</sup> recorded significantly higher grain yield as compared to other fertilizer levels [62].   |
| <b>C.</b>        | <b>Rice varieties recommendation</b>   |
| <b>Bangalore</b> | • Sharada (MAS 946-1) derived from parent lines IR64/ Azucena//IR64 and released for Zone-5 IET 17,164 in 2008. It has a 120–125-day duration, and grain yield ranges from 5.0–5.5 t ha <sup>-1</sup> . It has special features viz, water saving up to 60 %; seed saving (80 %), i.e. seed rate is 7 kg ha <sup>-1</sup> ; tolerant to moisture stress [87].<br>• MAS 946-1 genotype [88] as well as IRRI 14 genotype [89]; KRH-2 and MTU-1001 ( <a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a> ) were recommended due to the higher root traits, yield components, and yield.<br>• MAS25, MAS26, and MAS109 are water-efficient aerobic rice genotypes developed at UAS, Bangalore [51].  |
| <b>Mandya</b>    | • Cultivars recommended for cultivation by different researchers are Doddabyranellu [49]; Onasiri (MAS -26); Anagha (BI-33) and Sadruda (KMP175) [87]. They have special features viz, water saving up to 60 %; seed saving (7 kg ha <sup>-1</sup> ); tolerance to moisture stress and are released for Z 4 & 5(2008) IET 17,164 in 2008.  |
| <b>Shimoga</b>   | • BI-43 is recommended because of high yield potential combined with characteristics viz, long slender, light yellowish brown grains [82].   |
| <b>D.</b>        | <b>Irrigation and weed management</b>  |
| <b>Bangalore</b> | • Soil needs to be kept aerated to get the advantage of aerobic cultivation. Water can be provided twice a week, depending on soil type and rainfall. There is no need for maintaining soil at 'field capacity' ( <a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a> )<br>• In weed management, net returns and B: C ratio were maximum with pyrazosulfuron ethyl at 30 g a.i. ha <sup>-1</sup> compared to 2 hand weeding [90].  |

(continued on next page)

Table 2 (continued)

| Location       | Recommended management practices   |
|----------------|--|
| Mandya         | <ul style="list-style-type: none"> <li>The advantage was reported for disturbing soil between two crop rows by inter-cultural operations and added to the base of the rice plants so as to aerate the soil and reduce yield loss due to weed infestation (<a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a>)</li> <li>Effective weed control was obtained with pre-emergent application of bensulfuron methyl + pretilachlor (6.6 GR) @ 0.06+0.60 kg a. i. ha<sup>-1</sup> + one inter-cultivation at 40 DAS (or without HW) [83].</li> <li>Pyrazosulfuron ethyl (30 g a.i./ha) and two hand weeding at 20 and 45 DAS were on par with each other in controlling weeds, increasing yield and higher nutrient uptake by crop [57,89].</li> <li>Oxyfluorfen 200 g a.i. ha<sup>-1</sup> + FYM @ 10 t ha<sup>-1</sup> and Hand weeding 30 &amp; 45 DAS were found significant in recording higher grain yield [91].</li> </ul> |
| Uddebhonehalli | <ul style="list-style-type: none"> <li>Aerobic rice + coriander with inter cultivation at 30 and 50 DAS and aerobic rice + butachlor at 1 kg a.i. ha<sup>-1</sup> with intercultivation at 30 and 50 DAS are best practices for higher grain yield [81].</li> </ul>  |
| Mugad          | <ul style="list-style-type: none"> <li>Higher grain yield was obtained with the application of Mon 46,992 @ 2.5 l ha<sup>-1</sup> at 12–14 days after sowing [92].</li> </ul>  |
| G. Bangalore   | <p><b>Plant protection</b></p> <ul style="list-style-type: none"> <li>Prophylactic sprays of one dose of any systemic insecticide needs to be sprayed based on ETL (<a href="http://aerobicrice.in/practices.html">http://aerobicrice.in/practices.html</a>)</li> </ul>  |
| Shimoga        | <ul style="list-style-type: none"> <li>Dust bioagents (viz., <i>T. viride</i>, <i>P. fluorescence</i>, <i>P. lilacinus</i> and <i>P. chlamydozporia</i>) @ 2.0 kg each acre<sup>-1</sup> along with a nematocidal i.e., carbofuran 3 G 15.0 kg acre<sup>-1</sup> was recommended to control insect pest attack to aerobic rice ([93]).</li> </ul>  |

the ideal spacing.

### 3.2.2. Water management

The transplanted puddled rice approach, which is labor and water-intensive, is frequently used to grow rice. A severe water shortage is likely to occur by 2025, making it challenging to manage the available water for various needs [63]. Therefore, there is a requirement to develop and disseminate water-saving rice management practices. One of the long-term solutions that can help farmers cope with water scarcity in traditional rice-growing areas is the adoption of the aerobic/regenerative rice cultivation method [64]. In Karnataka, aerobic rice cultivation was observed to consume 45 to 55 % less water compared to transplanted puddled rice in the summer season, and with good rainfall distribution, it may be entirely rainfed during the wet season [52,65].

The water productivity in an aerobic rice system (0.45–0.55 g grain/litre of applied water) is about 50 % more than transplanted puddled rice [66,67]. According to Predeepa [68] (Fig. 6), the water requirement of aerobic rice may be significantly lower than that of Puddled rice because (1) water is not used to prepare wetland (puddling); (2) there are no ongoing percolation and seepage losses from the ponded water layer; and (3) there are no evaporation losses from the layer of ponded water [69]. Puddled and aerobic rice habitats differed significantly in terms of evapotranspiration and energy balance (Table 3). Aerobic rice is one of the innovative approaches for reducing the water required for rice crops, thereby alleviating water scarcity. However, in this study, due to the extremely low grain yields of aerobic rice resulting from water stress, the crop water productivity (WPET) of aerobic rice was much lower than that of flooded rice [70]. Further, differences in soil type, cultivar, climate, nitrogen regime, irrigation thresholds, weed control, and residue management can influence crop water productivity and yield. Understanding their impact is crucial for optimizing regenerative rice system practices. This information should be considered when assessing various water-saving methods for environmentally sustainable rice production systems.

For aerobic rice systems, irrigation was optimal at intervals of up to 25 days every five days, every five to seven days up to fifty days, and three days during the grain-filling stage [71]. In Karnataka, [67,72] the

resource use efficiency (RUE) of aerobic and puddled transplanted rice fields were compared. According to their findings, the physical and economic water use efficiency of aerobic farms (3.84 q/acre inch and 1643.54 rupees/acre inch) was higher than that of transplanted puddled rice farms (1.64 q/acre inch and 269.41 rupees/acre inch). The water productivity of aerobic rice varieties fluctuates between 0.42 and 0.47 kg/m<sup>3</sup> with irrigation at 20 kPa soil moisture potential (SMP) and between 0.50 and 0.55 kg/m<sup>3</sup> at 40 kPa SMP [58,73] also reported that aerobic rice cultivation is a feasible alternative to traditional rice (transplanted puddled rice) production in semi-arid regions, allowing significant water savings of 37 % to 45 %. Overall, our analysis of 16 studies (Table 4) revealed that regenerative rice systems led to a median water conservation of 52.5 % (interquartile range: 45 % to 60 %;  $n = 16$  comparative experiments). Soil type and climate also influenced water conservation, with greater savings observed in regions with limited water availability. Thus, regenerative rice is a viable option where more water is needed to grow lowland rice.

### 3.2.3. Intercropping

Several studies have reported that the efficient utilization of resources leads to yield advantages [74,75]. Compared to a sole or pure stand of a crop, the crops in intercropping use the available resources for plant growth and development, such as light, water, and nutrients, more effectively and have higher resource use efficiency [76,77]. Intercropping is the best choice for Karnataka farmers (Table 2) to plant more than one rice crop in a single season, as it increases their income due to their smaller land holdings. Regenerative rice offers a new scope to introduce intercrops on par with other arable crops, in addition to the advantages of reduced water requirement, improved root respiration, enhanced tillering, and high yield [78]. Growing short-duration vegetables in aerobic rice is a recent advancement to fulfill the requirement of vegetables and food grains without reducing the agricultural area [79]. A study on the weed dynamics, root characters, and nutrient uptake in aerobic rice with intercropping systems revealed the lowest dicot, monocot, and total weed density and biomass, higher root length, number, weight, and volume, which assisted in absorbing a larger share of nutrients from deeper soil resulting in increased nutrient uptake, with rice + amaranthus as compared to other intercropping systems [80,81]. The other researchers make several implications for intercropping in regenerative rice cultivation illustrated in Table 5.

### 3.2.4. Nutrient management

Achieving a balance between the nutrients that soils recover and the nutrients required by plants is essential for long-term agricultural output [94]. The switch from puddled rice to aerobic rice farming has caused alterations to the soil's chemical, biological, and physical characteristics, resulting in a scarcity of iron (Fe). Restrictions on the use of organics and insufficient recycling of crops remain compounded deficiencies in this type of rice production. Site-specific nutrition management (SSNM) is a novel approach to packaging management concepts. By limiting excessive and insufficient nutrient inputs, SSNM prevents the indiscriminate use of nutrients and promotes soil health over an extended period [67, 95]. In aerobic rice system, increased agronomic efficiency, recovery efficiency, partial factor productivity values of nitrogen, the yield and yield parameters were observed with the combined application of silicon (@ 2 t ha<sup>-1</sup>) and nitrogen (LCC-based application of 75 kg N ha<sup>-1</sup> in three splits of 15 kg N ha<sup>-1</sup> each time), when compared to the recommended dose of N 100 kg ha<sup>-1</sup> applied in three splits [96]. In comparison to applying urea, 17: 17: 17 (complex), and ammonium sulfate, the use of large-sized urea granules increased grain production, water use efficiency, energy output, input ratio, gross revenue, and B: C ratio [71].

The application of 10 tonnes FYM per ha with the recommended dose of fertilizers (100:50:50 kg N:P:K ha<sup>-1</sup>) led to significantly higher root volume and root dry weight [85,87] and higher total dry matter at harvest, higher nitrogen, phosphorus, and potassium uptake [86,87]. Rice grown aerobically showed a positive association between grain

**Table 3**

Energy balance, evapotranspiration, and crop water productivity between transplanted puddled rice and regenerative rice fields.

| Parameter                      | Transplanted Puddled Rice                | Regenerative Rice Fields                | Findings  |
|--------------------------------|--|---|---|
| Sensible Heat Flux (H)         | Lower                                    | Higher (45 % more)                      | Aerobic fields have higher H due to the presence of less water.                                   |
| Latent Heat Flux (LE)          | Higher (19 % more)                       | Lower                                   | Puddled fields have higher LE due to the increased availability of water for evapotranspiration.  |
| Evapotranspiration (ET)        | Higher (4.29 ± 0.23 mm d <sup>-1</sup> ) | Lower (3.81 ± 0.21 mm d <sup>-1</sup> ) | Puddled fields have higher ET rates due to ponded water and higher leaf area index.               |
| Crop Coefficient (Kc)          | Higher                                   | Lower                                   | Indicates higher water use efficiency in puddled rice during various growth stages.               |
| Crop Water Productivity (WPET) | Higher (1.26 ± 0.26 g/kg)                | Lower (0.42 ± 0.03 g/kg)                | Puddled rice is more productive per unit of water used, despite higher ET.                        |
| Energy Balance Closure         | Improved to 0.99 ± 0.01 after correction | Same as Puddled                         | The Bowen ratio closure method was used to correct H and LE values for accurate estimation of ET. |
| Annual ET                      | 1440 mm                                  | 1301 mm                                 | Puddled rice has about 11 % higher total ET than aerobic rice.                                    |
| Bowen Ratio                    | Lower (0.14 ± 0.03)                      | Higher (0.24 ± 0.01)                    | Indicates a difference in energy distribution between latent and sensible heat.                   |

Source – [70].

yield and total N, P, and K uptake [84]. It was found that using organic sources (farmyard manure, vermicompost, and chicken manure) individually or in combination with 75 percent RDF of nitrogen generated improved grain and straw yield with a higher harvest index, indicating a superior nutrient management approach for aerobic rice [97]. Additionally, the jeevamrutha application of vermicompost, equivalent to 10 tonnes of FYM and 100 percent N, increased the microbial population [87]. In addition to grain productivity, the integrated package of agro-techniques had a substantial impact on grain quality indices {100:50:50:30 NPK and Zn + FYM 10 t ha<sup>-1</sup> + Biofertilizers (soil application of *Azospirillum* and PSB (*Bacillus megaterium*) 4 kg ha<sup>-1</sup> each mixed with 8 kg of FYM) + Integrated weed management (Pyr-azosulfuron @ 25 g ha<sup>-1</sup> pre-emergence + HW @ 20 DAS)} except cooking quality parameters [83]. Biochar is a carbon-rich compound that improves paddy soil properties by increasing microbial activity and nutrient availability, accelerating the carbon and nitrogen cycle, and amending soil to sequester carbon [12,98,99]. The utilization of biochar in regenerative rice cultivation proved a superior option for enhancing nutrient use efficiency and maintaining soil health.

Apart from macronutrient deficiency, some micronutrient deficiencies are also present in rice; for instance, zinc deficiency is the common micronutrient deficiency happening in all methods of rice

**Table 4**

Meta-summary of Moderators.

| Moderator                          | Outcome           | n_studies | Median_pct | IQR_low_pct | IQR_high_pct |
|------------------------------------|-------------------|-----------|------------|-------------|--------------|
| Overall (pooled across moderators) | Water Saving      | 16        | 52.5       | 45.0        | 60.0         |
| Overall (pooled across moderators) | Methane Reduction | 9         | 56.0       | 34.0        | 78.0         |
| Overall (pooled across moderators) | Energy Reduction  | 9         | 24.5       | 6.4         | 42.5         |

The table below is structured to report median effects and interquartile ranges (IQR) by moderator level for the key outcomes (% vs transplanted puddled rice): water saving, methane reduction, and energy reduction.

cultivation (such as grown in lowland, upland, or aerobic conditions) [24,100,101]. In Karnataka and other parts of India, such a situation may occur. Combined application of RDF (100:50:50 N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O kg ha<sup>-1</sup>) + FYM @ 10 t ha<sup>-1</sup> with ZnSO<sub>4</sub> @ 20 kg ha<sup>-1</sup> + VAM + *Azospirillum* + PSB observed noticeably increased grain yield, nitrogen uptake, soil residual status, root weight, root volume, and root length [102]. In aerobic rice grown on upland alkaline and calcareous soils, iron (Fe) deficiency is also one of the serious nutritional disorders that cause a decline in rice productivity. Such deficiencies will not be there in puddled rice cultivation. However, rice varieties differ in their tolerance to Fe deficiency [103]. Therefore, in Karnataka and other parts of India, future research efforts are needed to improve genetics and enhance fertilization (both soil and foliar applications) to overcome nutrient deficiencies and thereby increase yield under aerobic conditions. Implications from various researchers for nutrient management in regenerative rice cultivation have been illustrated in Table 6.

### 3.2.5. Weed management

Weed infestation is one of the main obstacles to achieving a greater output under regenerative rice cultivation due to the exposure of land area during initial crop growth stages. Besides, alternate wetting and drying followed in aerobic rice cultivation are more favorable for weed growth. In aerobic soil conditions, both weed and rice germinate simultaneously, and from the time of emergence, competition for resources starts between the crop and weeds [90,104,105]. Such competition severely threatens rice crops during the early seedling growth and further development stages. Moreover, weeds are responsible for about 70–80 percent of yield losses or, in severe conditions, may lead to complete crop failure [105,106]. Hence, an effort to reduce weed menace by controlling weeds and thus providing a proper environment for rice crops to utilize the resources more efficiently would improve the yield. Thus, one of the critical cultural inputs needed for the aerobic method of rice establishment is regular weeding [61]. Hand weeding is complicated at the early stages of growth because the seedlings of grassy weeds and rice share morphological similarities [107]. Additionally, timely manual weeding of aerobic rice is impossible in Karnataka (and other parts of India) due to a lack of available labor and rising labor costs [20], necessitating the use of herbicides. Therefore, chemical weed control has emerged as a practical, cost-efficient, and effective choice. However, to effectively manage weeds during the aerobic rice crop growth stage, pre-emergence and post-emergence herbicide applications are necessary [108]. The details of herbicides found to be effective, as well as information on weeds and weed management in rice in Karnataka using chemicals such as herbicides, are presented in Table 3. By controlling weeds with a pre-emergence application of bensulfuron methyl + pretilachlor (6.6 GR) @ 0.06 + 0.60 kg ha<sup>-1</sup> + one inter-cultivation at 40 days after planting, higher net returns and a B: C ratio were attained [83].

### 3.2.6. Disease and pest management

The disease and insect pest management options available for puddled paddy, which are suitable for managing disease and insect pests, are also applicable to regenerative rice. According to a study [109] on the effect of meteorological variables on yellow stem borer- *Scirpophaga incertulas* infection in aerobic rice, borer infestation peaked during the Kharif and Rabi seasons 60 and 75 days after sowing, respectively.

**Table 5**  
Findings and implications for intercropping in regenerative rice cultivation.

| Study Reference | Study Objective  | Methodology  | Main Findings  | Implications for Intercropping in Regenerative Rice  |
|-----------------|--|--|--|--|
| [79]            | <ul style="list-style-type: none"> <li>To evaluate the efficiency and productivity of rice cultivation in various intercropping systems and irrigation regimes.</li> </ul>   | <ul style="list-style-type: none"> <li>A field experiment with six irrigation regimes and three cropping systems (Rice alone, Rice + Greengram Rice + Blackgram,)</li> </ul>   | <ul style="list-style-type: none"> <li>Maximum growth and yield with IW/CPE ratio of 1 for 60 days.</li> <li>Aerobic rice alone had higher growth and yield. LER indicated that both intercropping systems were advantageous.</li> </ul>   | <ul style="list-style-type: none"> <li>Indicates potential benefits of intercropping with pulses.</li> <li>Suggests optimal irrigation strategies for maximizing yield in intercropped systems.</li> </ul>   |
| [131]           | <ul style="list-style-type: none"> <li>To investigate the impact of intercropping peanuts with rice on the yield of rice in aerobic irrigation systems.</li> </ul>   | <ul style="list-style-type: none"> <li>Experiment was conducted using a split-plot design with two treatment factors. intercropping (with/without peanuts) and rice row patterns (single, double, triple)</li> </ul> | <ul style="list-style-type: none"> <li>Additive intercropping with peanuts resulted in increased red rice yield parameters, including clump size, filled panicle number, total biomass, panicle length, grain yield per clump, filled grain number, dry straw weight, and harvest index. Rice row patterns affected some yield parameters.</li> <li>Intercropping showed the highest benefits in single-row patterns.</li> </ul>   | <ul style="list-style-type: none"> <li>Suggests that intercropping with legumes can significantly enhance red rice yields.</li> <li>Provides insights into optimizing row patterns for maximizing yield benefits in intercropping systems.</li> </ul>  |
| [132]           | <ul style="list-style-type: none"> <li>To assess the microbial load of soil under different aerobic rice-based intercropping systems</li> </ul>  | <ul style="list-style-type: none"> <li>Field experiment with two land configuration methods (including raised bed) and five rice-based intercropping systems in sandy loam soils, using drip fertigation</li> </ul>  | <ul style="list-style-type: none"> <li>Significant variations in microbial population due to land configuration methods and intercropping systems.</li> <li>Raised bed configuration resulted in higher microbial populations (bacteria, fungi, actinomycetes). Aerobic rice with soybean intercropping showed the highest microbial population.</li> </ul>  | <ul style="list-style-type: none"> <li>Indicates that raised bed cultivation and specific intercropping systems (e.g., with soybean) enhance soil microbial load.</li> <li>Suggests that such practices could be beneficial for soil health and fertility.</li> </ul>                                    |
| [133]           | <ul style="list-style-type: none"> <li>Investigate the impact of planting soybeans as an additive crop on the yield of rice under aerobic conditions.</li> </ul>   | <ul style="list-style-type: none"> <li>Field experiment in Indonesia, using split plot design with two treatment black-rice genotypes and intercropping (monocrop vs. rice-soybean intercropping)</li> </ul>         | <ul style="list-style-type: none"> <li>When black rice was intercropped with soybean, there was an increase in growth and yield parameters. The average grain yield was higher in intercropped plots.</li> <li>Genotype G4/15 showed the highest response to intercropping.</li> <li>Interaction between genotypes and intercropping indicated varied responses.</li> </ul>  | <ul style="list-style-type: none"> <li>Suggests benefits of intercropping with soybean for improving black rice yield.</li> <li>Indicates the importance of selecting suitable rice genotypes for intercropping.</li> </ul>  |
| [134]           | <ul style="list-style-type: none"> <li>To investigate effect of planting peanuts in between rows of red rice on its growth and yield in an aerobic irrigation system.</li> </ul>                                       | <ul style="list-style-type: none"> <li>Field experiment using split plot design with two treatment factors: red rice genotypes and intercropping (monocrop vs. rice-peanut intercropping)</li> </ul>                 | <ul style="list-style-type: none"> <li>Rice-peanut intercropping increased rice growth and yield.</li> <li>Different rice lines showed varied responses to intercropping.</li> <li>Genotype G21 had the highest yield increase when intercropped with peanut.</li> <li>Plant height and grain yield were affected by both genotype and intercropping treatment.</li> </ul>   | <ul style="list-style-type: none"> <li>Indicates that intercropping with peanuts can enhance the yield of red rice, with varying effectiveness across different rice genotypes.</li> <li>Suggests genotype-specific approaches for optimizing intercropping benefits in red rice cultivation.</li> </ul> |
| [135]           | <ul style="list-style-type: none"> <li>To investigate impact of intercropping peanuts and the long-term application of organic wastes on mycorrhizal development and growth of red rice in aerobic systems.</li> </ul> | <ul style="list-style-type: none"> <li>Field experiment in Indonesia: intercropping with peanut and application of organic wastes</li> </ul>   | <ul style="list-style-type: none"> <li>Intercropping with peanut and application of organic wastes (especially rice husk ash) enhanced growth and mycorrhizal development in rice.</li> <li>Highest growth rates observed with rice husk ash application.</li> </ul>   | <ul style="list-style-type: none"> <li>Highlights the synergistic impact of intercropping with peanut on red rice growth.</li> <li>Supports sustainable practices in rice cultivation.</li> </ul>  |
| [136]           | <ul style="list-style-type: none"> <li>To assess both the agricultural and financial impacts of planting aerobic rice in combination with leafy vegetables through intercropping.</li> </ul>                           | <ul style="list-style-type: none"> <li>Field experiments at the UAS, Bangalore, India, using a Completely Block Design with 9 treatments (4 intercropping and 5 sole crops)</li> </ul>                               | <ul style="list-style-type: none"> <li>Intercropping, particularly rice-spinach intercropping, has shown to be more beneficial for plant growth and yield than sole cropping.</li> <li>Rice-spinach intercrop has been found to have the highest yield, land equivalent ratio, rice equivalent yield, production efficiency, area time equivalent ratio, and system harvest index.</li> <li>Net return and benefit-cost ratio were also higher in rice-spinach intercropping.</li> </ul> | <ul style="list-style-type: none"> <li>Demonstrates productivity &amp; economic efficiency of intercropping aerobic rice with vegetables,</li> </ul>   |
| [137]           | <ul style="list-style-type: none"> <li>To assess the impact of irrigation scheduling and intercropping on the yield, WUE, and economics of aerobic rice.</li> </ul>  | <ul style="list-style-type: none"> <li>Experiment was conducted at TNAU, India, with three replications focusing on different IW/CPE ratios and intercrop practices</li> </ul>                                       | <ul style="list-style-type: none"> <li>Optimal irrigation scheduling showed higher yield attributes and economic returns. The highest water use efficiency was recorded at an IW/CPE ratio of 1.0 up to maturity.</li> <li>Rice + black gram (2:1 ratio) intercropping system had higher</li> </ul>  | <ul style="list-style-type: none"> <li>An intercropping of rice and green gram in a 2:1 ratio was found to yield lower results in terms intercropping system of rice and black gram in the same ratio resulted in higher economic benefits.</li> </ul>   |

(continued on next page)

Table 5 (continued)

| Study Reference | Study Objective   | Methodology  | Main Findings  | Implications for Intercropping in Regenerative Rice  |
|-----------------|---|--|--|--|
| [138]           | <ul style="list-style-type: none"> <li>To evaluate the impact of intercropping rice with leafy vegetables on weed management</li> </ul>   | <ul style="list-style-type: none"> <li>Experiments at ZARS, UAS, Bengaluru, India, on red sandy loam soil using a completely block design with nine treatments (rice intercropped with four leafy vegetables and sole crops)</li> </ul>              | <p>economic returns, despite lower yield and WUE.</p> <ul style="list-style-type: none"> <li>Intercropping with leafy vegetables, especially palak (spinach), reduced weed density. Enhanced growth and yield of vegetables in intercropping systems compared to sole rice crops.</li> <li>Highest net monetary returns were recorded in rice-spinach intercropping.</li> </ul>    | <ul style="list-style-type: none"> <li>The net income of this system was recorded as ₹92,404 per hectare, with a B:C ratio of 2.43.</li> <li>Demonstrates the effectiveness of intercropping in weed management and improving crop yield and economic returns.</li> </ul>  |
| [139]           | <ul style="list-style-type: none"> <li>To investigate the impact of different cultivation techniques on growth and yield of Aerobic red rice</li> </ul>   | <ul style="list-style-type: none"> <li>Field experiment in Indonesia, arranged in a split plot Design with cultivation technique (conventional, aerobic rice systems, aerobic intercropped with peanuts) and rice row patterns as factors</li> </ul> | <ul style="list-style-type: none"> <li>Aerobic Red rice under showed higher growth and yield.</li> <li>Significant effects on yield components, such as panicle and filled grain number per clump.</li> <li>Interaction effect on filled grain number, indicating the positive effect of relay planting peanuts between rows of red rice.</li> </ul>                               | <ul style="list-style-type: none"> <li>Suggests that aerobic irrigation systems, particularly with peanut intercropping, enhance red rice growth and yield.</li> </ul>   |
| [140]           | <ul style="list-style-type: none"> <li>To investigate the yield, nutrient uptake, and economic impact of intercropping on aerobic rice.</li> </ul>  | <ul style="list-style-type: none"> <li>Field experiment during the Kharif season in a farmer's field, focusing on different intercropping systems with aerobic rice</li> </ul>   | <ul style="list-style-type: none"> <li>Higher rice grain yield and yield attributing parameters were observed in sole aerobic rice and rice + amaranthus intercrop.</li> <li>Rice + amaranthus showed high rice equivalent yield and nutrient uptake.</li> <li>Rice + amaranthus had significantly higher economic returns compared to other intercrops and sole crops.</li> </ul> | <ul style="list-style-type: none"> <li>Indicates the agronomic and economic benefits of intercropping, particularly with amaranthus.</li> </ul>  |
| [141]           | <ul style="list-style-type: none"> <li>To investigate the impact of intercropping rice with <i>Pontederia cordata</i> on rice plant growth, yield, pest control, grain quality, and income</li> </ul> | <ul style="list-style-type: none"> <li>Field experiments conducted over two years in 2016 and 2017 on rice-<i>Pontederia cordata</i> intercropping.</li> </ul>   | <ul style="list-style-type: none"> <li>There was a significant reduction in rice diseases and pests, with a 22.0–45.9 % decrease in sheath blight and a 33.8–34.4 % decrease in leaf folders. Positive yield effects with a mean LER of 1.09.</li> <li>Intercropping increased total income by 2.5 times over rice monoculture.</li> </ul>   | <ul style="list-style-type: none"> <li>Rice-<i>Pontederia cordata</i> intercropping is an effective method for controlling rice pests and diseases.</li> <li>Higher overall productivity, improved grain quality, and total income, suggesting economic and environmental benefits of this intercropping system</li> </ul> |

Moreover, there is a significant positive correlation between the infestation of stem borer and sunshine hours in *Kharif*. The morning and afternoon relative humidity exhibited a significant positive association with the percentage of dead heart or white ear heads, while the mean daily sunshine hours during the *Rabi* season did not show a significant correlation [110]. Also studied the seasonal fluctuation of Yellow Stem Borer on Paddy and its relationship with weather parameters. Another study by [61] on the effectiveness of various insecticides against *S. incertulas* on rice (cv. Rasi), fipronil 0.3 G (7.5 g active ingredient ha<sup>-1</sup>) had the lowest percentages of dead heart (DH) damage at 50 and 75 days after sowing (DAS), the lowest incidence of white ear heads, the highest grain and fodder yields.

Rice is often attacked by the rice root-knot nematode, which is scientifically known as *Meloidogyne graminicola*, and can cause several symptoms. The plant's roots may develop characteristic galls that resemble hooks, rings, or spindle-shaped beads/nodules. This can lead to stunting, chlorosis, wilting, and a delay in flowering by up to 15 days. In addition, the number of tillers and grains produced by the plant can be reduced. *M. graminicola* and *M. triticozyae* are two of the 14 species of nematodes that cause the most damage to rice crops grown in aerobic conditions in India [111–113]. Initially, rice root-knot nematode was noticed only in aerobic conditions. Since 2011, it has been observed in anaerobic conditions and appears in all rice-cultivating situations. In 2001, Shimoga saw the disastrous emergence of the rice root-knot nematode, the first report from Karnataka [113]. The knowledge from this study on nematodes is still inadequate, as evidenced by the abrupt breakout of *M. graminicola* infestation in a 1500 ha area in Mandya district (Karnataka, India) in the month of Kharif 2001 [114].

### 3.3. Climate change and rice cultivation: implications for mitigating methane emission reduction

Climate change is an overarching environmental crisis characterized by shifts in long-term weather patterns, and at its core is the phenomenon of global warming fueled by elevated levels of greenhouse gases (GHGs). In recent decades, global warming, due to increased GHG emissions, has become a serious environmental concern [115]. These increasing concentrations of GHGs pose a significant threat to the natural ecological balance and biogeochemical cycles, including rainfall, which in turn influences crop production [115]. Puddled rice cultivation is a significant source of methane (CH<sub>4</sub>) emissions, a potent GHG with a considerable contribution to climate change [116,117]. Approximately 10 to 12 percent of the world's total CH<sub>4</sub> emissions are attributed to rice farming [118]. Studies estimate that CH<sub>4</sub> emissions from rice cultivation in India range from 8 to 30 million metric tons annually [119,120]. Hence, methane emissions from rice paddies contribute significantly to greenhouse gas emissions. Transplanted rice cultivation in puddled soil conditions is one of the major sources of methane, which has a 28 times higher global warming potential (GWP) compared to CO<sub>2</sub> [118]. Studies have revealed that the heat-trapping potential of CH<sub>4</sub> is 21 times greater than that of CO<sub>2</sub> [121]. In addition, the atmospheric concentration of CH<sub>4</sub> has been increasing for several decades, and this upward trend has intensified since 2007 [122]. Global average mole fractions of methane reached about 1912 ppb (parts per billion) in 2022 and is 263% of pre-industrial levels [123,124]. When organic matter is exposed to methanogenic bacteria in an oxygen-restricted environment, such as puddled soil in paddy fields, CH<sub>4</sub> is released into the atmosphere [125, 126]. Several factors influence methane emissions from rice field. Water

**Table 6**  
Implications for Nutrient Management in Regenerative Rice.

| Study Reference | Study Objective  | Methodology   | Main Findings  | Effects of Nutrient Management in Regenerative Rice  |
|-----------------|--|---|--|--|
| [142]           | <ul style="list-style-type: none"> <li>To evaluate the impact of silicon and phosphorus fertilization on aerobic rice's growth, productivity, and profitability.</li> </ul>                | <ul style="list-style-type: none"> <li>Field experiment testing four levels of phosphorus and silicon in a FRBD</li> </ul>  | <ul style="list-style-type: none"> <li>Highest grain yield, net returns, and yield attributes were observed with 90 kg P<sub>2</sub>O<sub>5</sub>/ha and were at par with 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. In the case of silicon</li> </ul>                                      | <ul style="list-style-type: none"> <li>Highlights the significant role of phosphorus and silicon in enhancing productivity and profitability.</li> <li>Appropriate application rates of these nutrients can lead to improved growth and yield</li> </ul>   |
| [143]           | <ul style="list-style-type: none"> <li>To assess the effect of different nutrient management practices on growth and nutrient uptake in aerobic rice</li> </ul>                            | <ul style="list-style-type: none"> <li>Field experiment with eleven different nutrient management practices, including RDF, RDF + Vermicompost, RDF + FYM, and others, in an RBD design.</li> </ul> | <ul style="list-style-type: none"> <li>Highest grain yield with NPK + Vermicompost + ZnSO<sub>4</sub> + Borax treatment.</li> <li>Organic substitutions like FYM and Vermicompost alone did not significantly impact growth, yield, or nutrient uptake compared to combined treatments.</li> </ul> | <ul style="list-style-type: none"> <li>Highlights the efficacy of combined inorganic and organic nutrient management practices for improving yield and nutrient uptake.</li> </ul>   |
| [144]           | <ul style="list-style-type: none"> <li>Evaluate the quality of aerobic rice under different site-specific nutrient management approaches</li> </ul>  | <ul style="list-style-type: none"> <li>Field experiment with four aerobic rice genotypes and three target yield levels in a BRD.</li> </ul>   | <ul style="list-style-type: none"> <li>Higher protein content and overall better quality in specific genotypes (MAS 946-1, MAS 77) under targeted higher yield levels.</li> <li>Variations in protein and amylose content noted with different nitrogen levels for targeted yields.</li> </ul>     | <ul style="list-style-type: none"> <li>Suggests that genotype selection and site-specific nutrient management significantly influence the quality attributes.</li> </ul>   |
| [145]           | <ul style="list-style-type: none"> <li>To evaluate Jeevamruta as a bio-resource for nutrient management in aerobic rice</li> </ul>   | <ul style="list-style-type: none"> <li>Field experiment with treatments including Jeevamruta, vermicompost, biofertilizers, and chemical fertilizers in red sandy loam soil.</li> </ul>             | <ul style="list-style-type: none"> <li>Highest grain yield with RDF + Jeevamruta + Vermicompost + Biofertilizers.</li> <li>Jeevamruta worked well in integration with chemical fertilizers, especially in combination with RDF.</li> </ul>   | <ul style="list-style-type: none"> <li>Jeevamruta is an efficient bio-resource when used with RDF, potentially improving yield and soil health.</li> <li>Integrated nutrient management with Jeevamruta and biofertilizers can enhance economic efficiency.</li> </ul>   |
| [146]           | <ul style="list-style-type: none"> <li>To investigate the impact of nutrient and weed management on crop yield and soil microbial properties in aerobic rice farming.</li> </ul>           | <ul style="list-style-type: none"> <li>Factorial RBD design experiment with three levels of nutrient management and five levels of weed management at ICAR-IARI, New Delhi.</li> </ul>              | <ul style="list-style-type: none"> <li>100 % RDF and 75 % RDF + Biofertilizer showed higher growth and grain yield. Highest soil microbial biomass with 75 % RDF + BF. Weed management with Bispyribac + mulch and Sesbania + HW showed significant benefits.</li> </ul>                           | <ul style="list-style-type: none"> <li>Integrated approach with 75 % RDF + Biofertilizers and effective weed management strategies like Bispyribac + mulch can enhance both crop productivity and soil microbial health.</li> </ul>  |
| [147]           | <ul style="list-style-type: none"> <li>To evaluate the economic feasibility and productivity of aerobic rice through lateral arrangement and nutrient management.</li> </ul>               | <ul style="list-style-type: none"> <li>Strip plot design experiment with three lateral arrangements and four nutrient management strategies at I.G.K.V, Raipur.</li> </ul>                          | <ul style="list-style-type: none"> <li>Higher growth parameters and grain yield under lateral arrangement at 25 cm (M1). STCR-based fertilizer application showed the best results among nutrient management treatments.</li> </ul>  | <ul style="list-style-type: none"> <li>Optimal lateral arrangement and tailored nutrient management, particularly STCR-based fertilization, are crucial for maximizing productivity. Lateral spacing and precise nutrient management catered to specific field conditions can lead to improved yield and potentially better economic returns.</li> </ul> |
| [148]           | <ul style="list-style-type: none"> <li>To assess the economic viability and productivity of aerobic rice cultivation by optimizing nutrient management and lateral arrangement.</li> </ul> | <ul style="list-style-type: none"> <li>Recent advances in nitrogen cycle pathways under aerobic rice system &amp; agronomic management approaches to enhance NUE.</li> </ul>                        | <ul style="list-style-type: none"> <li>Highlighted the challenge of low NUE and high nitrogen losses in aerobic rice. Suggested strategies include optimized nitrogen fertilizer amendments, site-specific Nitrogen management (INM, and other resource conservation practices.</li> </ul>         | <ul style="list-style-type: none"> <li>Emphasizes the need for integrated and optimized nitrogen management approaches to enhance NUE in aerobic rice, ensuring sustainable productivity and environmental safety.</li> </ul>  |
| [149]           | <ul style="list-style-type: none"> <li>To evaluate the impact of irrigation and nitrogen management on water productivity and nutrient absorption of aerobic rice.</li> </ul>              | <ul style="list-style-type: none"> <li>The experiment with three water management treatments and four nitrogen management strategies.</li> </ul>  | <ul style="list-style-type: none"> <li>Highest grain yield obtained with 125 % CPE irrigation and 100 % N through fertilizers. The highest NPK uptake was noted with 100 % N treatment.</li> </ul>   | <ul style="list-style-type: none"> <li>It indicates that specific water and nitrogen management combinations can optimize grain yield and nutrient uptake, with potential improvements in water productivity and economics.</li> </ul>   |

management practices, including continuous flooding, contribute to the anaerobic conditions necessary for CH<sub>4</sub> production [120]. Additionally, the decomposition of organic matter, nutrient availability, soil characteristics, and rice cultivars also play significant roles in CH<sub>4</sub> emissions from rice fields [127].

Methane emissions from rice cultivation exhibit regional variations within India [128] evaluated methane (CH<sub>4</sub>) emissions under different rice establishment methods and found that Direct-Seeded Rice reduced methane emissions by approximately 34.56 % compared to Transplanted Rice, making it a promising strategy for lowering greenhouse gas emissions from paddy fields. A meta-analysis by [129] synthesizing data from 54 peer-reviewed studies found that DSR significantly reduced methane (CH<sub>4</sub>) emissions by 70 % compared to TPR. Additionally, the global warming potential (GWP) was lowered by 37 %, and the carbon

footprint (CFP) decreased by 34 %, showing the environmental sustainability of DSR [130] examined methane emissions in aerobic rice systems using subsurface and surface drip irrigation (SDI & DI). They reported a 78 % reduction in CH<sub>4</sub> emissions compared to conventional flooded aerobic irrigation. The study further revealed that CO<sub>2</sub>-equivalent emissions (CO<sub>2</sub>-eq) were reduced by 43.8 % under SDI and 25.1 % under DI. The nine most relevant studies (Table 4) suggested that regenerative rice led to a mean reduction of methane emissions of 56 % (interquartile range: 34 % to 78 %; n = 9 comparative experiments) compared to puddled transplanted rice. However, the effects varied by cropping systems and other land management practices.

Mapping was conducted to estimate the rice area under various rice ecologies throughout India in 2020 (Fig. 7). It was found that India is home to diverse rice ecologies, each adapted to specific regions and

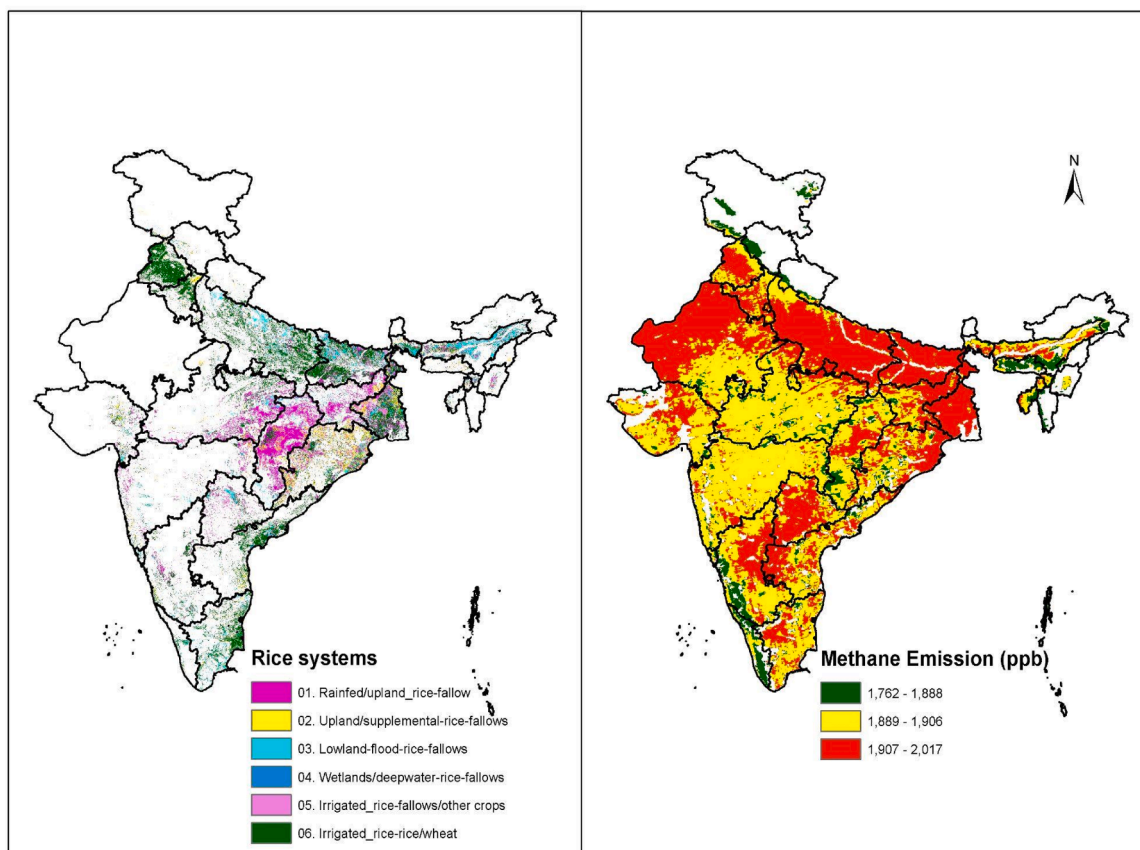


Fig. 7. Different rice ecologies and methane emissions over India in 2020.

climatic conditions. The Indo-Gangetic plains, due to their fertile alluvial soil, practiced irrigated rice-rice/wheat systems. In the areas of Chhattisgarh and Jharkhand, a rainfed rice fallow or other crop system is followed. Upland rice is also cultivated in some parts of Haryana, Punjab, West Bengal, and Odisha. Lowland paddy rice is also present in some parts of India. The study also analyzed atmospheric methane concentrations over India in 2020 (Fig. 7). We found higher atmospheric CH<sub>4</sub> concentrations over different rice ecologies to other parts of India. The highest atmospheric concentration of methane, about 2000 ppb, was observed over IGP and some parts of Chhattisgarh and Telangana in 2020. In all these places, rice is one of the dominant crops. Studies have also shown higher emissions in the eastern and northeastern regions, where traditional lowland rice cultivation methods are prevalent [119, 127]. These emissions contribute significantly to the country's overall GHG inventory and highlight the need to address this issue for sustainable agriculture and climate mitigation. There are several efficient soil, water, and fertilizer nutrient practices such as zero-tillage [98], deep placement of ammonia, intermittent irrigation, system of rice intensification, etc. can significantly lower greenhouse gas emissions, especially methane, in rice production.

Conventional Puddled (transplanted puddled) rice cultivation creates anaerobic soil conditions, thereby promoting methane production. While regenerative rice cultivation, which keeps the soil well-aerated, is being explored as a more environmentally friendly alternative. Several studies have demonstrated that transitioning from constantly puddled paddies to an intermittent irrigation and drainage schedule can significantly reduce methane emissions. For instance, study in Nanjing, China, showed that methane emissions from intermittently drained fields were reduced considerably (60 %) over the continuously puddled fields [150]. Additionally, producing rice in upland regions with aerobic fields produces significantly less methane per hectare. Several implications have been made for rice practices to mitigate methane emissions from

various research studies, as shown in Table 7. Regenerative rice cultivation has potential to mitigate methane emissions and contribute to climate change mitigation efforts.

#### 3.4. Energy consumption rates in transplanted puddled rice and regenerative rice system

Ecosystems that utilize energy and the degree of automation determine the amount of energy used. Indeed, different production systems consume different levels of energy in paddy cultivation. Fuel used in the puddled system is more diesel energy. Comparing direct seeding rice (DSR) or aerobic rice to the puddled system, less diesel fuel is required in DSR because there is no rice nursery tillage operation or nursery field preparation [154]. Field preparation requires significant energy, as the transplanting technique necessitates an additional farm border, thereby increasing diesel fuel consumption [155,156]. Rice seedlings were raised in puddled soil during the transplanting procedure. As a result, the transplanting system requires a lot of water, increasing the electricity needed to pump water for extended periods. While crops require 45 % less water in aerobic conditions than transplanting systems, they are a suitable way to enhance energy consumption efficiency in rice fields. Reduced irrigation energy consumption increases rice production energy efficiency [157]. Further, in the puddled system, labor is used for all seedling establishment tasks, including sowing and transplanting seedlings from the nursery to the main field. It makes sense that the puddled system requires a lot of human labor to produce rice. The degree of mechanization of a farming system often has a negative relationship with the amount of human work required, as a more mechanized farm requires less labor [158]. Due to the intense workload and financial strain that the puddled method imposes on rice growers over a brief period (10–20 days), farmers are more likely to opt for the direct seeding method [154]. Aside from equipment, seed, and fertilizer,

**Table 7**  
Implications of Regenerative Rice Practices to Mitigate Methane Emissions.

| Study Reference | Study Objective   | Methodology  | Main Findings   | Implications for Mitigating Methane Emissions in Rice Cultivation  |
|-----------------|---|--|---|--|
| [151]           | <ul style="list-style-type: none"> <li>To study how soil tillage and nitrogen fertilizer management affect methane emissions from rice fields.</li> </ul>   | <ul style="list-style-type: none"> <li>A field experiment was conducted using a split-plot design to compare different tillage and nitrogen fertilizer management methods, including deep placement of tablet urea, prilled urea, and ammonium sulfate.</li> </ul> | <ul style="list-style-type: none"> <li>Compared to maximum tillage, no-tillage reduced methane emissions by 15.58 %, but resulted in lower grain yield (2.73 t/ha vs 3.68 t/ha). AS and tablet urea deep placement resulted in lower methane emissions and higher grain yield.</li> </ul>   | <ul style="list-style-type: none"> <li>Implementing no-tillage practices can effectively reduce methane emissions, though with a trade-off in grain yield.</li> <li>Deep placement of ammonium sulfate and tablet urea fertilizers offers a promising strategy to simultaneously enhance rice productivity and mitigate methane emissions from rice fields</li> </ul>  |
| [151]           | <ul style="list-style-type: none"> <li>To study the impact of water management on methane emissions and rice yield in East Asia's paddy fields.</li> </ul>  | <ul style="list-style-type: none"> <li>Meta-analysis of 161 water management and 174 rice yield observations from 28 articles at a regional scale.</li> </ul>  | <ul style="list-style-type: none"> <li>Water management practices reduced methane emissions in paddy fields by 60.5 %.</li> <li>Rice yield decreased by 5.8 %, but the reduction was insignificant.</li> <li>Practices that reduce methane emissions without affecting yields include alternating wet and dry, flooding-drainage-reflooding, and moist irrigation.</li> </ul> | <ul style="list-style-type: none"> <li>Implementing AWD, FDF, and MI water management practices can reduce methane emissions without significantly impacting rice yields.</li> <li>Suitable for application in regions with similar conditions to Korea, providing a basis for developing unique coefficients for predicting methane emissions and rice yields in future water management strategies.</li> </ul> |
| [152]           | <ul style="list-style-type: none"> <li>The study compared the effectiveness of intermittent irrigation and continuous flooding in reducing methane and nitrous oxide emissions from rice fields in Brazil and Japan.</li> </ul> | <ul style="list-style-type: none"> <li>Comparative assessment using field experiments to evaluate CH<sub>4</sub> and N<sub>2</sub>O emissions under intermittent irrigation and continuous flooding</li> </ul>   | <ul style="list-style-type: none"> <li>Continuous puddled soils emitted more methane in Japan than in Brazil.</li> <li>Intermittent irrigation reduced soil CH<sub>4</sub> emissions by up to 71 % in Japan and 62 % in Brazil.</li> <li>No significant difference in N<sub>2</sub>O emissions or rice yield between irrigation systems.</li> </ul>                           | <ul style="list-style-type: none"> <li>Intermittent irrigation is a more efficient practice than continuous flooding in reducing methane emissions without impacting rice yield.</li> <li>These practices can be applied in countries like Brazil and Japan to lower greenhouse gas emissions from rice fields.</li> </ul>   |
| [153]           | <ul style="list-style-type: none"> <li>To assess the impact of crop management practices and nitrogen fertilization on yield and GHG emissions in rice production in Tanzania.</li> </ul>                                       | <ul style="list-style-type: none"> <li>Experiments compared conventional rice cultivation and SRI at varying nitrogen fertilizer rates in a split-plot randomized complete block design.</li> </ul>  | <ul style="list-style-type: none"> <li>Methane emissions were higher in conventional practice than in SRI.</li> <li>SRI reduced CH<sub>4</sub> and CO<sub>2</sub> emissions significantly over CP.</li> <li>The interaction of SRI and 90 kg N/ha resulted in higher grain yields with low global warming potential and GHG intensity.</li> </ul>                             | <ul style="list-style-type: none"> <li>System of Rice Intensification (SRI) combined with optimized nitrogen fertilization (90 kg N/ha) can significantly reduce greenhouse gas emissions while maintaining or improving rice yield. This approach is effective for climate-smart rice cultivation and reducing the environmental impact of rice production.</li> </ul>  |
| [128]           | <ul style="list-style-type: none"> <li>To investigate the potential of direct-seeded rice (DSR) in reducing greenhouse gas (GHG) emissions compared to transplanted rice (TPR).</li> </ul>                                      | <ul style="list-style-type: none"> <li>A field experiment in Central Java, Indonesia, comparing methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions, yield, and global warming potential (GWP) under DSR and TPR conditions.</li> </ul>          | <ul style="list-style-type: none"> <li>Methane emissions were 47 % lower in DSR (187 kg CH<sub>4</sub> ha<sup>-1</sup> season<sup>-1</sup>) compared to TPR (352 kg CH<sub>4</sub> ha<sup>-1</sup> season<sup>-1</sup>), with no significant impact on grain yield.</li> </ul>  | <ul style="list-style-type: none"> <li>DSR is a promising low-emission alternative to TPR, effectively mitigating CH<sub>4</sub> emissions while maintaining yield stability.</li> </ul>   |

the energy consumption estimates of the two rice production methods differed significantly; however, in the direct seeding cultivation technique, more energy was used for herbicides [154]. Researchers studied energy consumption (Table 8) in puddled transplanted rice (under anaerobic conditions) and the regenerative rice system/direct-seeded rice (under aerobic conditions). The nine relevant case studies (Table 4) demonstrated that regenerative rice systems led to a mean reduction in energy intensity of 24.5 % (interquartile range: 6.4 % to 42.5 %;  $n = 9$  comparative experiments) compared to puddled, transplanted rice. For sustainable progress, energy resources must be used as efficiently as possible. Therefore, the transformation of the puddled rice system into a regenerative rice system enhances resource use efficiency.

#### 4. Limitations and research gaps

Our analysis of regenerative rice systems highlights its potential to mitigate climate change, improve water use efficiency, and reduce energy consumption. However, several limitations and biases must be acknowledged, including regional data concentration with much emphasis on India/Karnataka, short observation periods, heterogeneity in CH<sub>4</sub> measurement methods, potential underestimation of N<sub>2</sub>O, and changes in soil carbon balance.

Research gaps include the need for long-term field series, limited geographic coverage, poor integration of satellite observations with

ground-based fluxes, and a lack of data on the economics of adoption and farmer behavioral barriers. Assessing the total climate effect in CO<sub>2</sub> equivalent is crucial, considering tradeoffs between CH<sub>4</sub> decline and potential N<sub>2</sub>O increases, as well as impacts on soil carbon stocks. A systems perspective recognizes the interconnectedness of biophysical and socioeconomic factors that influence regenerative rice systems, informing strategies to enhance adoption, mitigate potential negative consequences, and promote sustainable agricultural practices. By addressing these limitations and gaps, we can gain a deeper understanding of the potential of regenerative rice systems to contribute to sustainable agriculture and mitigate climate change.

#### 5. Systems thinking to promote regenerative rice system

Our review of regenerative rice systems highlights its potential to conserve water, reduce energy intensity, and mitigate methane emissions while maintaining crop yields. However, to fully realize these benefits, it's essential to consider the broader systems context. The impact of the regenerative rice system extends beyond farm-level benefits, influencing water budgets at the basin level, biodiversity, and soil health. Effective management of water resources, including investment in efficient irrigation systems, is crucial to ensure sustainable water use. The adoption of regenerative practices can be enhanced through targeted scaling mechanisms. Demonstration farms can showcase the

**Table 8**

Energy consumption ( $\text{MJ ha}^{-1}$ ) in transplanted puddled rice (TPR) and regenerative rice systems (RRS).

| Case Studies  | Rice system | Total energy input (MJ/ha) | % decrease in energy consumption over PTR | Reference |
|---------------|-------------|----------------------------|---|-----------|
| Case-1        | TPR         | 50,022*                    | 30.9                                      | [154]     |
|               | RRS         | 34,543                     |   |           |
| Case-2        | TPR         | 19,170                     | 42.5*                                     | [159]     |
|               | RRS         | 11,031                     |   |           |
| Case-3        | TPR         | 32,418                     | 13.1                                      | [160]     |
|               | RRS         | 28,175                     |   |           |
| Case-4        | TPR         | 38,879                     | 30.4                                      | [161]     |
|               | RRS         | 27,069                     |   |           |
| Case-5        | TPR         | 33,158                     | 31.6                                      | [162]     |
|               | RRS         | 22,683                     |   |           |
| Case-6        | TPR         | 21,724                     | 8.4                                       | [163]     |
|               | RRS         | 19,906                     |   |           |
| Case-7        | TPR         | 32,360                     | 7.4                                       | [164]     |
|               | RRS         | 29,970                     |   |           |
| Case-8        | TPR         | 25,185                     | 23.7                                      | [165]     |
|               | RRS         | 19,206                     |   |           |
| Case-9        | TPR         | 21,900                     | 6.4                                       | [166]     |
|               | RRS         | 20,500                     |   |           |
| Mean          |             | 27,106                     | 22  |           |
| Range         |             | 11,031–                    | 6.4–42.5                                  |           |
|               |             | 50,022                     |   |           |
| SD            |             | 8754                       | 12  |           |
| SEm ( $\pm$ ) |             | 2063                       | 3   |           |
| CV (%)        |             | 32                         | 57  |           |

SD: standard deviation; SEm: standard error mean; CV: coefficient of variation; \*: indicates highest.

benefits of regenerative practices, while digital agricultural consulting can provide farmers with personalized advice and support. Additionally, subsidies and insurance products can help mitigate risks and incentivize farmers to adopt regenerative practices.

However, a comprehensive decision-making framework is necessary to balance biophysical effects with economic and risk considerations for different farm categories. This framework should account for factors such as farm type, climate, soil, and economic costs to ensure that regenerative practices are tailored to specific contexts. By integrating systems thinking and a decision-making framework (Fig. 8), we can develop targeted strategies to promote regenerative rice systems, ensuring sustainable agriculture practices that benefit both farmers and the environment.

## 6. Conclusions

Around 25 % of anthropogenically induced greenhouse gas (GHG) emissions originate from agriculture and land-use changes. Traditional rice cultivation, characterized by puddled conditions, has a negative environmental impact by releasing substantial amounts of  $\text{CO}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{CH}_4$ . Methane is primarily emitted from puddled rice fields, exacerbating concerns about global warming. Additionally, traditional management practices, including soil puddling, improper chemical use (such as fertilizers/herbicides/pesticides), and excessive water stagnation throughout crop growth, are damaging land productivity, soil health, and resource efficiency, thereby threatening the sustainability of rice systems. Globally, boosting rice productivity while managing scarce irrigation water availability (during land preparation and crop growth stages), reducing labor, addressing low soil fertility, and increasing pest outbreaks have emerged as significant challenges for farmers. Regenerative management techniques, such as aerobic/regenerative rice systems, offer a sustainable approach to ensuring future rice productivity. Under ideal circumstances, the yield gap between regenerative and traditional puddled rice systems could be bridged, and their productivity could be improved sustainably due to improved soil health. Regenerative rice cultivation eliminates the need for seedling transplantation, reduces irrigation during land preparation and crop growth (a 45–60 % reduction in water consumption), fosters a strong rice root system, and lowers labor costs throughout the entire process from seeding to harvest. Transitioning from conventional puddled to regenerative (aerobic) rice systems reduces overall energy use, attributed to a 6.4–42.5 % decrease in energy consumption due to lower electricity requirements for water pumping, reduced diesel consumption for tillage, improved irrigation methods, and lower labor expenses. Regenerative rice systems help farmers increase rice grain productivity and encourage them to adopt energy-efficient rice production methods. Moreover, it promotes environmental sustainability in the context of current climate change by reducing greenhouse gas emissions, explicitly achieving a 34–78 % decrease in methane emissions. This will contribute to sustainable development goals (SDGs) viz. SDG-2 (Zero Hunger), SDG-12 (Responsible Production and Consumption), SDG-13 (Climate Action), and SDG-15 (Life on Land). These technologies are most replicable in areas with the right climate, soil types, and levels of automation. Areas with significant water constraints, high methane emission potential, efficient rice cultivars, and land degradation neutrality should be given priority for immediate implementation. Future studies should focus on standardizing field measurement procedures, expanding to

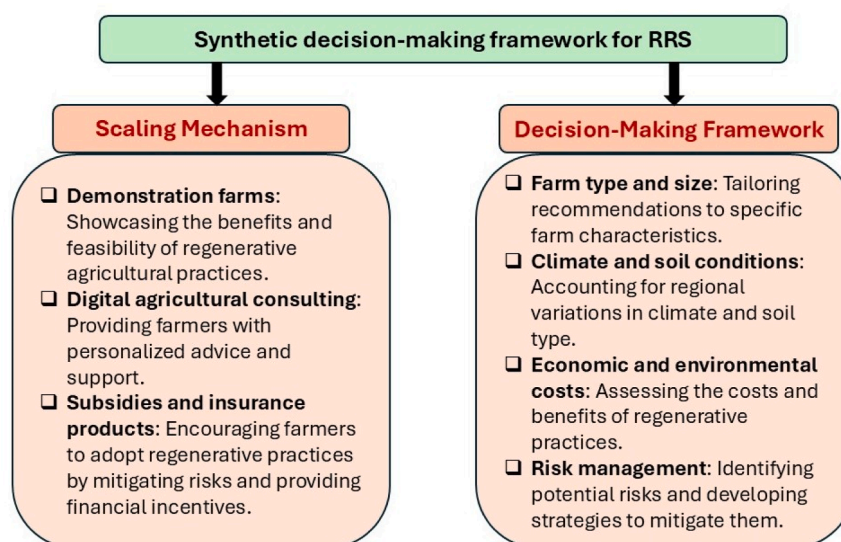


Fig. 8. Synthetic decision-making framework for scaling RRS.

underrepresented areas, qualitatively validating satellite-based methane indicators, and assessing the environmental and economic impacts of transitioning to regenerative rice cultivation.

## 7. Way forward

Regenerative rice system is a technology that needs further research and refinement to be widely adopted across different agro-ecologies in India and the World. This review summarizes the advantages of regenerative rice over puddled rice. We also demonstrated the crop management practices under regenerative rice through a case study of Karnataka, India, and supported by several global research studies. The current review also provides the environmental benefits of adopting regenerative rice. We recommend some key points from this review to assist the scientific community and policymakers in making informed decisions that promote regenerative rice cultivation locally, nationally, and globally.

- Large-scale on-farm and farmer participatory validation trials are essential to demonstrating the benefits of regenerative rice technologies to farmers and enhancing the adoption of regenerative rice cultivars and management practices.
- Uncertainty about rainfall and irrigation water availability necessitates breeding rice cultivars capable of stabilizing performance under fluctuating conditions prevailing in regenerative rice growing environments. This requires substantive effort in rice breeding, local adaptation, and dissemination.
- If needed, intensive research efforts are required to fine-tune technologies for regenerative rice and identify economical, ecologically safe, and economically viable management options for managing weed, disease, and insect pests.
- Efforts to enhance the efficiency of other resources (land, nutrients, etc.) from a system perspective while minimizing environmental footprints are to be worked out.
- In the era of scarce and costly labor, regenerative rice offers excellent opportunities for utilizing machinery throughout the crop cultivation phases. However, farmers must be trained to optimize energy usage in rice production systems.
- An imperative investigation into greenhouse gas (GHG) mitigation through regenerative rice cultivation is essential to quantify its potential for mitigating GHG emissions compared to traditional transplanted puddled rice methods.
- Recent technologies, such as remote sensing, should be deployed to map the traditionally transplanted rice area for shifting towards regenerative rice systems.

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## Data availability statement

The authors will make the raw data supporting this article's conclusion available without undue reservation.

## CRedit authorship contribution statement

**G.L. Sawargaonkar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Conceptualization. **S. Rakesh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis. **S. Kale:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision. **P.J. Kamdi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision. **V. Padmaja-Karanam:** Writing – review & editing, Writing – original draft. **R. Pasumarthi:** Writing – review & editing, Writing – original

draft. **P. Choudhari:** Writing – review & editing, Writing – original draft. **A. Singh:** Writing – review & editing, Writing – original draft. **M. Patil:** Writing – review & editing, Resources. **M.K. Gumma:** Writing – review & editing, Resources. **R. Singh:** Supervision, Project administration. **A.K. Padhee:** Writing – review & editing, Resources. **M.L. Jat:** Writing – review & editing, Supervision, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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