Paddy and Water Environment
https://doi.org/10.1007/s10333-024-00989-3

ARTICLE

Green manuring–system of rice intensification–rice fallow pulses cropping system for enhancing the crop productivity and soil health: a sustainable farming solutions

S. Marimuthu[1] · **M. Gunasekaran**[1] · **M. Raju**[2] · **U. Surendran**[3,4]

Received: 1 July 2023 / Revised: 1 May 2024 / Accepted: 2 June 2024

Abstract

Rice cultivation in Tamil Nadu, a southern state of India, is a vital component of its agricultural landscape and economy. It holds historical significance and contributes significantly to the state's food security. Green manuring–system of rice intensification (SRI)–blackgram (rice fallow pulses) cropping system is novel, and this integrated system appears to be holistic and sustainable approach, combining innovative farming techniques to optimize yields, improve soil health, and minimize environmental impacts. To evaluate this, field demonstrations were conducted at a farmer's field through the National Pulses Research Centre, Vamban, Pudukkottai, Tamil Nadu, within the *kharif rabi* and summer seasons of 2019–20 under the Tamil Nadu Irrigated Agriculture Modernization project. The experimental site was medium deep clay with soil pH of 8.51, EC of 0.26 d S m^{-1}, low in available nitrogen (212.02 kg ha^{-1}), high in P_2O_5 (23.24 kg ha^{-1}), and medium in K_2O (300.46 kg ha^{-1}). Initially, farmers were given the awareness about the improved production technologies (IPT), and then, demonstration was conducted in 50 hectares with 92 locations of Ponnaniyar sub-basin. The demonstration results showed that the improved practice of SRI recorded higher plant height and other yield attributes. Notably, the SRI cultivation method exhibited a range of yields from 7580 to 9400 kg ha^{-1} of rice across various locations, with the highest recorded at Avoor village. Concurrently, within the IPT framework for the GM–SRI–Rice fallow pulses cropping system, the recorded yields for Rice fallow Blackgram ranged from 590 to 730 kg ha^{-1}. Comparative analysis indicated a remarkable 39.9 percent enhancement in system productivity through the adoption of IPT practices compared to conventional farmer practices. Moreover, the IPT framework showcased significantly higher water productivity, recording 0.7087 kg ha^{-1} m^{-3} compared to the conventional method, which yielded 0.2512 kg ha^{-1} m^{-3}. Soil nutrient observations highlighted that these cropping systems positively impacted soil fertility parameters, compared to the initial available nutrient status. This augmentation in soil fertility could be attributed to the incorporation of green manures. Consequently, the green manure–system of rice intensification–rice fallow pulses crop sequences emerged as more productive and sustainable option, displaying the potential to enhance soil productivity and fertility status compared to conventional rice–blackgram/groundnut cropping sequences. These systems present promising alternatives for farmers within the Ponnaniyar sub-basin area of Tamil Nadu.

Keywords Crop yield · Blackgram · Rice · Green manure · Soil health · Economics · Water productivity

Introduction

Rice (*Oryza sativa* L.) was cultivated 7000 years ago in Assam–Meghalaya areas of India and in the mountain regions of Southeast Asia and Southwest China. Nearly 90 percent of the world's rice is produced and consumed in Asia, which accounts for nine of the top ten rice-producing countries across the globe. India is the largest rice growing country in the world with 42.5 million hectares area; however in production, it is second in the world with 152.6 million tonnes, the first being China with 206.09 million tonnes

---

✉ U. Surendran
suren@cwrdm.org

[1] National Pulses Research Centre, Vamban, Pudukkottai, Tamil Nadu, India

[2] Water Technology Centre, Tamil Nadu Agricultural University, Coimbatore, India

[3] Centre for Water Resources Development and Management, Calicut, Kerala, India

[4] Present Address: ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur, India

(FAOSTAT 2021). Rice stands as the predominant cereal crop in the Cauvery deltaic zone (CDZ) of Tamil Nadu, encompassing an area of 1.45 million hectares, equivalent to 11.13 percent of the state's total area.

Rice production in India has increased in past three decades continuously beginning with green revolution but stagnated since 1999. To meet the demand of growing population and maintaining self-sustainability, the present production level needs to be increased to at least 120 million tons by 2030 with an average productivity of 4.03 t ha^{-1}. The increase in production has to be achieved in the backdrop of declining and deteriorating resource based such as land (soil), water, labour, and other inputs without adversely affecting the quality of the environment. This is only possible through intensification of rice cultivation (Biswal et al., 2014). Cropping systems based on climate, soil, and availability of water have to be assessed for realizing the potential production levels through efficient use of available resources. The cropping strategy should ensure ample food provision for households, fodder for livestock, and generate the necessary revenue to cover domestic and agricultural expenses. In Tamil Nadu, the traditional cropping system of rice–rice–pulses demands substantial water for irrigation and nutrient input, resulting in escalated production costs, reduced grain yield, and a lower net income.

The lack of awareness and improper application of nutrient sources, coupled with limited use of organic materials, has led to soil deficiencies not only in essential nutrients but also in deteriorating overall soil health, and the same has been reported in many earlier studies (Babu et al. 2020; Sruthi and Surendran, 2023). Consequently, this has resulted in a decreased crop response to recommended fertilizer doses and diminished positive residual effects on maintaining soil fertility (Surendran et al. 2016). Specifically, cultivating rice–rice–rice crops exacerbates multi-nutrient deficiencies in soils, particularly within rice-based cropping systems. A declining productivity trend has been noted in extensive, long-term experiments across various regions in India involving these kinds of mono-cropping sequences.

Despite its extensive cultivation, the sole production of rice falls short of sustaining farmers' livelihoods within the Cauvery deltaic zone (CDZ). The reasons attributed are low productivity, monsoon failures, pest and disease infestation, labour shortage, etc. Consequently, farmers opt for rice fallow pulse cultivation as a residual crop, requiring minimal additional inputs besides essential agronomic practices like occasional weeding and limited irrigation. This kind of alternate agricultural practice serves as a main source of improved income for farmers during off-seasons or in instances of monsoon failure, bridging economic gaps. Among the various rice-based cropping systems tested, the rice–pulse combination emerges as one of the most prevalent and significant systems within the CDZ, particularly in the coastal ecosystems. TNAU and the Department of Agriculture are promoting such alternate rice based cropping systems to enhance the income of farmers and the cultivation of blackgram pulses within this system has gained a lot of attraction among CDZ farmers as a secondary crop after rice cultivation. Earlier studies showed that selection of blackgram pulses as a residual crop following rice cultivation aids in managing soil fertility levels effectively, especially within specific cropping sequences like rice–pulse (Senthilvalavan and Ravichandran, 2020).

In Pudukkottai district, rice and blackgram are cultivated in an area of 69,143 and 27,067 ha, respectively, and in Tiruchirappalli district 4649 and 3544 ha, respectively. Reasons for low productivity in rice fallow pulses are use of poor quality seeds, poor soil fertility status, low soil moisture availability, non-scientific irrigation management, improper weed management practices, non-availability of water, quality seed materials during the peak season, more incidence of mung bean yellow mosaic virus (MYMV) in the traditional varieties, partial adoption of seed treatment, poor plant population and non-adoption of integrated nutrient management and diammonium phosphate/TNAU pulse wonder and Planofix spray, etc. In a nutshell, many of the recommendations were not being followed by the farmers due to different reasons.

The potential for expanding rice cultivation areas diminishes, because of the pressure on land and hence it becomes imperative to improve the productivity per unit area and complement conventional breeding methods with innovative techniques. The pursuit of self-sufficiency in rice production and the maintenance of price stability are critical political goals in low-income countries. This is due to the pivotal role of rice in ensuring national food security, as well as in creating employment opportunities and generating income for low-income populations (Ghosh et al. 2009). In recent times, concerns have arisen regarding the plateauing yields in rice production and hence researchers are looking for novel initiatives. The System of Rice Intensification (SRI), pioneered by Father Heneri de Laulinie in Madagascar in 1983, has gained significant attention in India and other countries since 1997 as a yield improvement technology. Adoption of this method has the potential to approximately double average rice yields without necessitating changes in cultivars, reduction in water use and purchased inputs (Wang et al. 2003). The integration of new and improved technologies is expected to encourage farmers to discontinue conventional practices and transition to these advanced methodologies (Sharma et al. 2011; Surendran et al. 2021).

To address such challenges and objectives, a participatory field demonstration involving farmers was conducted to investigate the impact of the SRI method on growth, yield, and economic aspects of rice cultivation, aiming to replace conventional practices. The integrated cropping system of green manure–SRI–Pulses presents an alternative approach aimed at enhancing overall system productivity, reducing water demands, and revitalizing soil fertility. This system involves the incorporation of green manure (sunhemp—*Crotalaria juncea*) directly into the soil, followed by the cultivation of rice using the SRI method. SRI, differing from the conventional flooded rice cultivation, exhibits potential in mitigating challenges related to water scarcity, high energy consumption, and environmental degradation. Subsequently, a distinctive agricultural practice called "rice fallow pulse" is implemented post-Samba rice cultivation, occurring from January to March in the Ponnaniyar sub-basin area. This innovative approach capitalizes on the residual soil moisture available approximately 7–10 days before rice harvest. Under zero-tillage conditions, pulses, notably blackgram, are sown with the aim of optimizing the use of remaining soil moisture for successful crop establishment. Consequently, the current study focuses on the green manure–SRI–rice fallow blackgram cropping system to counteract the declining trend in soil fertility status.

Given these circumstances, it becomes imperative to integrate both organic and inorganic nutrient sources using a scientific approach to yield promising outcomes in rice-based cropping systems. This integrated approach aims to ensure sustained productivity while simultaneously promoting soil health (Senthilvalavan and Ravichandran, 2020). SRI-Rice fallow pulses (RFP) cropping system along with green manure is novel, and this integrated system appears to be holistic and sustainable approach, combining innovative farming techniques to optimize yields, improve soil health, and minimize environmental impacts. The main hypothesis of the farmer participatory demonstration is that SRI method, green manuring and rice fallow pulse will have a positive impact on growth, yield, and economic aspects of rice cultivation, and with these participatory demonstrations, it has been aimed to replace the conventional practices.

Materials and methods

Study area—overview of ponnaniyar

Ponnaniyar sub-basin lies in the south central part of Tamil Nadu (Fig. 1). Ponnaniyar sub-basin comes under the Cauvery river basin. It is bounded by the Bay of Bengal on the east and Palk straight on the south, Karur district on the west, Perambalur, Ariyalur districts on the north-west and Cuddalore district on the north. It has 10,375.94 ha ayacut

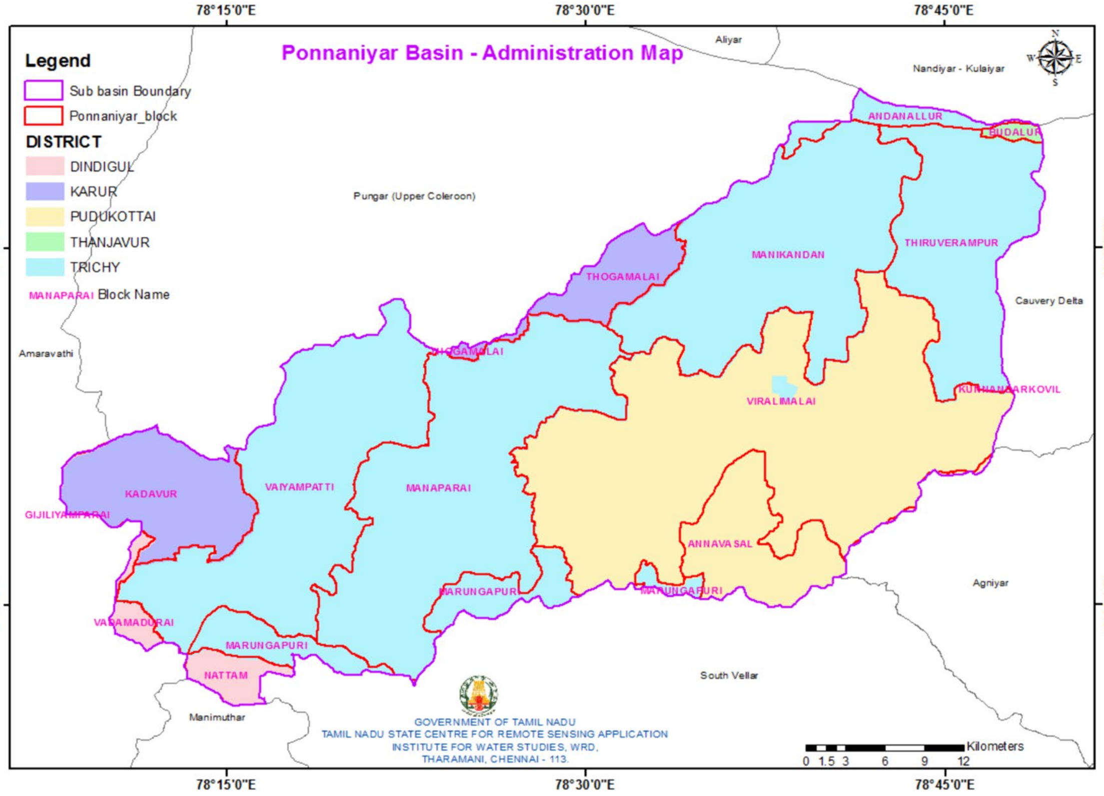

Fig. 1 Ponnaniyar basin—administrative map

Table 1 Basic information of the Ponnaniyar sub-basin in Pudukkottai and Tiruchirappalli districts

Geographical Position	Pudukkottai	Tiruchirappalli
North latitude	9° 50' and 10° 40'	10° 15’ and 11°20’
East longitude	78° 25' and 79° 15'	78° 10’ to 79° 50’
Total geographical area (Sq km)	4663.29	4,403.83
Fully irrigated area (ha)	1724.85	5775.26
Partially irrigated area (ha)	610.79	1409.89
Gap: fallow (ha)	547.70	2054.28
Total ayacut area (ha)	2883.34	7538.230
Rainfall pattern		
SW monsoon (June–Sep) (mm)	350.6	293.7
NE monsoon(Oct–Dec) (mm)	406.2	391.5
Winter (Jan–Feb) (mm)	33.1	22.7
Summer (Mar–May) (mm)	97.5	109.9
Total	887.4	817.8

area which comprises anicut, tanks, and direct ayacut. This sub-basin consists of six blocks, viz. Manapparai, Vaiyampatti, Manikandam, and Tiruverumbur in Tiruchirapalli district and Viralimalai and Annavasal in Pudukkottai district. This basin has 87 non-system and system tanks, 15 channels, and 14 anicuts (Table 1).

Methodology

The study was carried out through front line demonstrations (FLD) during *kharif*,*rabi* and summer season of 2019–2020 at three blocks, viz. Annavasal, Viralimalai blocks in Pudukkottai district and Manikandam block in Tiruchirappalli district under Ponnaniyar sub-basin of Tamil Nadu of with the active participation of farmers after different extension approaches through regular field visit and interpersonal communication made by the scientists and technical assistant of National Pulses Research Centre, Tamil Nadu Agricultural university, Vamban, Pudukkottai, Tamil Nadu, India.

The selected cropping sequence consists of Green manure (sunhemp), Rice (SRI), and Blackgram (RFP). Initially, sunhemp, a green manure, is cultivated and subsequently incorporated into the soil. Following this, rice is cultivated utilizing the System of Rice Intensification (SRI) method. Prior to the rice harvest, the subsequent crop of blackgram is cultivated. Mean maximum and mean minimum temperatures registered in the years were 38.30 °C and 27.60 °C; 39.60 °C and 28.5^{0}C of Pudukkottai and Tiruchirappalli districts, respectively. Totally 639.7 mm rainfall and 616.4 mm rainfall were received in Pudukkottai and Tiruchirappalli district, respectively, during the cropping period. The soil of the experimental site was normal to slightly sodic in reaction (pH 8.35 to 8.61), (EC 0.20 to 0.37dSm^{-1}), clay loamy texture with low to medium in nitrogen (128.75 to 350.00 kg ha^{-1}), low to high in phosphorus (10.00 to 38.75 kg ha^{-1}), and low to medium in potassium (193.75–398.44 kg ha^{-1}) contents. The demonstration was conducted in an area of 50 hectares with Ninety-two (92) farmers. The farmer’s practices involved conventional method of rice transplanting of 25-days-old seedlings with (15 × 10) cm spacing at the rate of 2–3 seedlings per hill, 2–4 cm standing water, chemical weeding by application of Butachlor. The improved practice of SRI included transplanting 12–14-days-old seedlings in (25 × 25) cm spacing at the rate of one seedling per hill, weeding by cono weeder with alternate wetting and drying-based irrigation and nitrogen application based on leaf colour chart (LCC). SRI results in reduced use of irrigation water and seed expenses and increase in the grain yield and maintenance of soil health. The crop was transplanted during 1st week September and harvested during 2nd week of January during the study period. Observations on different yield parameters and final crop yield (grain &straw) were taken, and economic analysis was performed by calculating cost of cultivation, gross return, net return, and cost–benefit ratio on the basis of prevailing market price of inputs and minimum support price of the produce.

Apart from SRI, two other improved practices, viz. Green manuring and Pulses, were also demonstrated. Green manure application involved the use of high-quality sunhemp (*Crotalaria juncea*) seeds at a rate of 50 kg ha^{-1}. These seeds were sown between June and July and incorporated into the soil at approximately 40–45 days after sowing (DAS) as part of the system of rice intensification (SRI).

Nursery management

The high-yielding rice variety TKM 13 was utilized with a seed rate of 7.5 kgha^{-1}, sown in a nursery area covering 2.5 cent ha^{-1}. The seeds were treated with *Pseudomonas* at a rate of 10 g per kg of seeds, while *Azospirillum* and *Phosphobacteria* were applied at 30 g each per kg of seed. To initiate the growth process, pre-sprouted seeds were planted on raised nursery beds, meticulously prepared to resemble garden crop beds. A fine layer of vermicompost, approximately 50 kgs, was applied, creating a base upon which the sprouted seeds were thinly distributed. Another layer of manure was then used to cover the seeds, followed by a mulch of paddy straw. Careful watering was performed using a rose cane to ensure optimal moisture content. Finally, banana leaf sheaths were employed to facilitate the easy lifting and transportation of the seedlings.

Main field preparation

Land preparation is similar to that of irrigated rice cultivation. However, levelling was done carefully so that water can be applied very evenly followed by formation of channels at every 3 m distance to facilitate drainage. Spacing followed was at intervals of 25 × 25 cm, and lines were marked in both directions, using a marker, creating a grid-like pattern. The seedlings were transplanted at the points where these lines intersect. The transplanting process involves the utilization of 14-days-old seedlings, which are transplanted systematically in a square planting pattern of 25 × 25 cm using a rice transplanter. Besides, it has been ensured that the optimal plant population is maintained, with approximately 16 plants per square meter.

Irrigation and water management

The purpose of irrigation is to wet the soil and saturate the soil with moisture, Subsequent irrigation is only when soil develops hair line cracks. The irrigation is followed as per the standard procedure of SRI-based rice cultivation. This kind of alternate wetting and drying of soil results in increased microbial activity in the soil and easy availability of nutrients to the plants.

Weed management

The absence of standing water in the system of rice intensification (SRI) tends to result in more weed growth. To address this issue, a cono weeder was employed at specific intervals: 10, 20, 30, and 40 days after transplanting. While weeding, the practice involved incorporating the weeds into the soil by manoeuvring the weeder between the rows. Weeds situated near the rice hills and tillers were removed by hand manually to ensure their optimal growth. Nitrogen application was carried out using the standard practice of LCC method.

For the cultivation of rice fallow pulse, specifically the Mungbean yellow mosaic virus-resistant Blackgram Var. VBN 8, seeds were utilized at a rate of 20 kg per hectare. These seeds were sown approximately 7 to 10 days before the rice harvesting period, when the soil was having enough moisture condition (waxy condition). This sowing timeframe spanned from the 15th of January to the 3rd week of February across all locations. The maintenance of an optimal plant population was ensured, targeting 32 plants per square meter. Before seeding, the seeds were treated with *Pseudomonas* at a rate of 10 g per kg of seeds, along with the application of bio-fertilizers such as *rhizobium* and *phosphobacteria*, each at 30 g per kg of seeds. During the growth stages, a 1% TNAU Pulse wonder solution was utilized for foliar spraying when the crop reached 50% flower initiation; it is a crop booster sprayed for enhancing the growth and more flower production in blackgram. Pest management strategies were implemented, employing pheromone traps at a rate of 12 traps per hectare against *Spodoptera* and applying Dimethoate at 500 ml per hectare to combat MYMV and leaf crinkle disease. At the harvesting stage, the seeds were dried until they reached below 10% moisture content and subsequently stored in gunny bags for safekeeping.

Observations recorded

Observations on growth and yield parameters for green manure (sunhemp)-rice (SRI)-blackgram (RFP) cropping system were recorded in *kharif*, *rabi* and summer seasons of 2019–20. For green manure biomass kg.m^{-2} at 45 days after sowing, for rice number of plants m^{-2}, plant height (cm) at harvest, number of productive tillers hill^{-1}, number of filled grains plant^{-1}, 1000 grain weight (g) and grain yield (kg.ha^{-1}) and for rice fallow blackgram plant height at harvest, number of branches per plant and pod length (cm) and yield parameters, viz. number of pods per plant, 100 grain weight and grain yield were recorded at maturity stage as per the standard procedures. The economic indicators of various treatments were worked out by using the current market price of inputs and blackgram yield.

Rice equivalent yield (REY)

Since various types of crops are included in cropping system, it becomes very difficult to compare to economic produce form a sequence with the other of a different nature. Efforts have been made to convert the yields of different crops into equivalent yield of anyone crop and in this case, rice being the major crop, rice is considered and computed the rice equivalent yield. Yield and yield parameters of rice and other crops in the cropping system were recorded. Economic yields of component crops were converted into rice equivalent yield (REY), taking into account the prevailing market prices of different crops in the cropping sequences. The REY values were computed as per the following formula given by Verma and Modgal (1983).

$$\text{Rice equivalent yield } \left(kg.ha^{-1}\right) = \frac{(YCC \times MPCC) + \text{Yield of main crop } \left(kg.ha^{-1}\right)}{\text{Price of main crop } \left(Rs.ha^{-1}\right)} \quad (1)$$

Table 2 Influence on improved production techniques on green manure–SRI–rice fallow blackgram of plant population, yield parameters, and water consumed (pooled mean of 92 locations)

Yield characters					
Biomass observation in green manure (Sunhemp)		System of rice intensification		Rice fallow pulses	
1. No. of plants m^{-2}	59	1. No. of plants m^{-2}	16	1. No. of pods plant^{-1}	39
2. Plant height (cm)	147	2. Plant height (cm)	73	2. No. of seeds pod^{-1}	7
		3. No. of productive tillers hill^{-1}	38.3		
		4. No. of filled grains plant^{-1}	1492		
3. Biomass weight(kg.m^{-2})	2	5.1000 grain weight(g)	23.5	3.100 grain weight	4.6
4. Green manure (Sunhemp) biomass yield (tonnes ha^{-1})	19,900	6. Grain yield (kg/ha) SRI	8355	4. Seed yield (kg.ha^{-1})	682
5. Water consumed (mm. ha^{-1})	232	7.Water consumed (mm. ha^{-1})	910	5. Water consumed (mm.ha^{-1})	404

where YCC = yield of component crop (kg ha^{-1}) and MPCC = market price of component crop (Rs. ha^{-1}).

The initial and post-harvest soil EC, pH, NPK were analysed using the following standard procedures, the available nitrogen by Subbiah and Asija 1956, available phosphorus by Olsen et al. 1954 and available potassium by Jackson 1973) .

The cost of cultivation was calculated each crop by taking account of prevailing market price of inputs. Local market price was used for grain of rice and blackgram and biomass of green manure (sunhemp) for calculating the gross return and net return. The cost of green manure biomass (sunhemp) is Rs. 0.50 kg^{-1}, rice grains Rs.19 kg^{-1}, and blackgram grains 50 Rs.kg^{-1} as the prevailing market rate.

Water productivity (Rs.ha^{-1} mm) was calculated as the ratio of gross income (Rs. ha^{-1}) and total water used. Extension gap was calculated by the formula suggested by Samui, et al. (2000).

$$\text{Extension gap} = \text{Demonstration yield} - \text{Farmers yield} \tag{2}$$

Results and discussion

The technology demonstrations on three crop sequence of green manure–system of rice intensification (SRI)–rice fallow pulses were implemented to increase the soil fertility and also crop productivity and farmers' income, and the results obtained were discussed.

Growth and yield parameters

Under improved production techniques (IPT), the sunhemp plants exhibited a significant increase and height was observed as 147 cm and this might be due to the enhanced growth and maintenance of an optimal plant population. Similarly, employing the System of Rice Intensification (SRI) led to a greater plant height of 73 cm, an increased number of productive tillers averaging 38.3, and a 1000 grain weight of 23.5 g in rice (Table 2). These favourable outcomes could be attributed to various factors, including seed treatment with bio-fertilizers such as *Azospirillum* and *phosphobacteria*, along with bio-inoculants like *Pseudomonas fluorescence*. Additionally, optimal fertilizer application, cono weeding practices, and efficient nitrogen management guided by the LCC contributed significantly to these improved results.

The incorporation of green manure within the crop sequence played a crucial role in preventing nutrient loss from the soil. Green manure plants have the capacity to draw nutrients from the soil and store them within their biomass. Upon decomposition and mixing into the soil, these plants release the stored nutrients, thus facilitating nutrient recycling and serving as a vital source of nutrients and energy for numerous beneficial soil organisms. Previous studies have demonstrated the release of nitrogen, phosphorus, and potassium in the soil through the decomposition of *Crotalaria juncea* L (Sinha et al. 2009). Ultimately, this might have helped by providing plant available nutrients and enhancing the growth parameters. However, it is noteworthy that the rate of nutrient release is significantly influenced by climatic factors like temperature and moisture (Sinha et al. 2009), as well as the types of plants (Saria et al. 2018). These findings align with similar conclusions presented by researchers such as Hosaain et al. (2003) and Gupta and Sharma (1991).

Number of pods per plant 39, number of seeds per pod 7, and 100 grain weight 4.6 g (Table 2) were observed in rice fallow blackgram in comparison with conventional method. The reason might be the seed treatment with *rhizobium* and *phosphobacteria* and bio inoculants, i.e. *Pseudomonas fluorescens*, proper irrigation during critical stages, especially flowering, pod formation, and development stages, foliar application of micronutrient and growth regulators and IPM practices for controlling of pest and diseases. The increase in grain and straw yields owing to vermicompost application could be ascribed to better mineralization, leading thereby to higher availability of nutrients, higher occurrence of beneficial micro-organisms, growth-promoting hormones, antibiotics as well as enzymes (Banik et al., 2006). Continuous supply of nutrients in balanced quantity throughout the growth stages enables the plants to assimilate sufficient photosynthetic product and thus increased dry matter accumulation. Therefore, implementation of improved production technologies produced more panicles and grains/panicle with increased test weight, resulting in higher grain yield (Sudhakar et al. 2006).

Biomass and grain yield

The rice and blackgram yield showed 26% and 25% increase in improved production technologies on GM–SRI–Rice fallow pulses system over the farmer's practices. In the Green manure–SRI–Rice fallow pulses system, the mean highest biomass yield of sunhemp 21,094 kg ha^{-1}, rice grain yield of 8480 kg ha^{-1} through SRI method, and 690 kg ha^{-1} of blackgram yield (Table 3) were obtained and it was higher than the conventional method of cultivation**.** Incorporation of sunhemp as crop residue enhances both crop productivity and enrichment of soil fertility as well as healthy environment by activating microbes, thus playing a major role in the sustainability of cropping systems. Incorporation of sunhemp can significantly increase rice yield and subsequent crop yield by substituting a part of inorganic fertilizers, while the increase of yield gains and reduction of fertilizer application may be location specific and improved agronomic practices (Shan Huang et al. 2013). This might be due to the production of higher number of effective tillers per plant and higher number of grains per panicle and grain yield which was in conformity with Maiti et al. (2003). *Sesbania aculeata* can be grown as green manure crop and helps in improving physical properties of soil including infiltration rate and soil organic carbon (Boparai et al. 1992). Most of these green manures, acknowledged for its capacity to form root nodules, fix nitrogen, and thrive in challenging conditions like waterlogged or drought-affected environments, has emerged as a yield enhancement strategy in sustainable agriculture (Ambika et al. 2015). Sunhemp stands out as the primary contributor among green manures in furnishing biomass and nitrogen to agricultural fields (Dubey et al. 2015). Moreover, *Crotalaria juncea*, commonly known as sunhemp or Tropic sun, is native to India and extensively cultivated in various countries. Often grown specifically for its role as green manure, it is recommended to plough sunhemp before reaching its full flowering stage. As a leguminous plant, *Crotalaria* is renowned for enriching the soil with nitrogen content for subsequent plants. However, studies indicate variations in nitrogen input when considering the addition of shoot, root, or both to the soil. Research demonstrated that the recovery rate of nitrogen was notably higher in subsequent plants when solely the root was incorporated compared to those with both shoot and root (Choi et al. 2008). The incorporation of *Crotalaria juncea* as a green manure crop not only enhances yield but also facilitates substantial nitrogen fixation, potentially offering ample nitrogen content to rice plants. Consequently, it stands as a viable alternative for rice farmers facing resource limitations (Dickmann et al. 1996).

In the modern days of agricultural science, crop rotation and green manuring (GM) offer a technology to achieve sustainable production efficiently. Since continuous intensive and conventional cultivation leads to a decline in soil organic matter content, soil nutrients and water holding capacity are affected severely, resulting in a loss of soil sustainability. One of the options to maintain sustainability in agriculture by restoring soil quality (especially in tropical soils) and reclaiming degraded soil is to increase soil organic matter content by green manuring (Kumar et al. 2010, 2014; Chimouriya et al. 2018) because this practice is eco-friendly, non-polluting, and non-hazardous to soil, water, and air (Yang et al. 2018). Therefore, for sufficient production of quality food grains and to feed ever growing population, green manuring practices are promising tools for the better sustainability of agriculture in the longer run and with almost no hazards to the environment (Kumar et al. 2014). Moreover, due to the continuous exertion of soil and incompetent methods of soil management like excessive tillage and burning of vegetative residues, exposure to climatic changes, the accelerated soil degradation has led to reduced crop production (Florentín et al. 2010). The soil management practices to increase fertility and productivity should include an increase in biomass along with reducing its decomposition (Bunch 2012). Green manuring, on the other hand, being a practice in which the undecomposed plant material is turned under the soil to provide organic material and nutrients to the soil, can be considered as a suitable alternative to positively affect the physical, chemical, and biological properties of the soil (Fageria 2007). Giving proper attention and gaining knowledge regarding the composition, rates and placement of green manure crops, the application of fertilizers can be reduced drastically (Schröder 2005) and in most of the cases fertilizers can be saved up to 30%. The potential of green manures is not limited to only improvement of soil quality and increasing the yields of subsequent crops, rather pest management and weed control has also been reported when green manuring practices are followed appropriately (Boydston and Hang 1995; Al-Khatib et al. 1997). However, the increased production cost of planting green manure led to minimize farmers' acceptance to this approach, which is showing a lack of support for its sustainability (Ntakirutimana et al. 2019).

Delay planting/sowing due to irregular onset of monsoon and non-availability of quality seed of suitable variety cause yield reduction in paddy and blackgram. Injudicious application of fertilizers and hand weeding by the farmers also cause the lower yield in rice (Samant 2015). However, in the current study, improved production technology resulted in higher yield. This corroborates the findings of the Central Rice Research Institute (CRRI) that hybrid Rajalaxmi are superior over Lalat (CRRI 2006). Thus, the large level demonstration might have a positive impact on farming community for increase the production in the district over conventional method of cultivation of rice and blackgram. Similar results were also reported by Mondal et al. (2005) in rice with different cropping systems.

Soil fertility status

Post-harvest soil pH, EC, available nitrogen, phosphorus, and potassium contents varied with all 92 locations of the GM–SRI–RFP cropping system. Overall mean of the post-harvest soil EC 0.29 dSm^{-1} and pH 8.02 were changed, when compared to initial soil EC of 0.26 dSm^{-1} and pH of 8.51. Highest soil available nitrogen and phosphorus and potassium was recorded with GM–SRI–RFP involving cropping systems such as sunhemp–rice–blackgram of 223.14, 27.76, and 312.11 kg ha^{-1} of N, P, and K, respectively, compared to initial soil available NPK status (212.02, 23.24, and 300.46 kg ha^{-1} of N, P, and K, respectively) (Table 4). Post-harvest available soil N, P, and K status was high with sunhemp–rice–rice fallow blackgram in the cropping system, even after the removal of adequate quantity of N by the succeeding rice. This might be due to considerable amount of N added through incorporation of biomass of sunhemp as a green manure and N fixed by the *rhizobial* nodules by rice fallow blackgram resulting in higher post-harvest available soil NPK. Moreover, large quantity of biomass added, its decomposition, synthesis and subsequent mineralization leads to improvement in the organic carbon status of the soil. Post-harvest available soil N, P, and K status was high with sunhemp–rice–rice fallow blackgram in the cropping system, even after the removal of adequate quantity of N by the succeeding rice. This could be ascribed to the increase in the available N, P, and K contents in soil resulting from the increased availability of nutrients which ultimately increased nutrient content in the plant tissues and greater biomass production at higher rates of fertilizer application. Since the uptake of nutrient is a function of dry matter and nutrients content, the increased grain and straw yields together with higher NPK content resulted in greater uptake of these elements (Balasubramaniyan, 2004; Surendran et al. 2016; Mishra et al. 2021). The release of organic acids has increased the soil phosphorus content, which in turn increased the availability of P_2O_5. The extensive root system of legume improved the physical condition of the soil and the liberated CO_2 and organic acids which might have helped in dissolving native potassium in soil and thereby increasing the availability of potassium (Shridhara et al. 2016). Soil available nutrient status was low due to exhaustive nature of the crop and non-contribution to soil nutrition with rice–rice cropping system (Mukundam et al. 2012). Similarly Porpavai et al., (2011) also reported that legumes were potentially important to diversify cereal based mono-cropping into cereal-legume sequences which had nutrient cycling advantages. An increased uptake of nitrogen, phosphorus, and potassium by rice might be due to constant release of nutrients that satisfied the demand of the hybrid rice at every stage of the crop (phenophase) as opined by Sudhakar and Kuppuswamy (2007). This could be attributed to the comparatively lower C/N ratio of vermicompost, which resulted in faster decomposition and release of nutrients as compared to farm yard manure (Pareek and Yadav 2011).

Organic anions arising from decomposition of organic matter form stable complexes with Fe^{3+}, Al^{3+} and prevent their reaction with phosphates ions and result in significantly higher available P due to organic sources. Soil exhibited significantly higher available K status under higher rates of organic sources as compared to medium and lower quantities. Most of the K in plants remains in organic form, and the decomposing organic matter may have a solubilizing effect on native soil potassium. These findings are in done conformity with Kharub and Chander (2008). However, N mineralization from GM plants is significantly influenced by soil characteristics such as pH and texture, management practices, climate, age of the plants, and their C/N ratio (Nagarajah et al. 1989; Singh et al. 1992; Kumar and Power 2018). P availability may be increased in soils of high P fixing capacity because P adsorption sites may be masked by organic compounds that are synthesized during GM decomposition (Easterwood and Sartain 1990). Moreover, organic compounds may also release P from adsorbed sites through anion exchange phenomenon (Kafkaf et al. 1988). Therefore, in general GM decreases soil P sorption (Singh and Jones 1976; Bumaya and Naylor 1988). This might be due to subsequent P sorption on soil and more utilization of available P by the soil microorganisms (White and Ayoub 1983).

Rice equivalent yield (REY)

The mean higher rice equivalent yield of 2766 kg ha^{-1} was obtained when green manure–rice–rice fallow pulses cropping system than the conventional system (Table 5). The highest REY was registered in Annavasal and Viralimalai blocks than Manikandam block, whereas minimum rice

Table 3 Influence on improved production techniques on green manure–SRI–rice fallow blackgram minimum, maximum and mean yield (pooled mean)

Name of the block/ village	Green manure Biomass yield (kg ha^{-1})			Rice grain yield (kg ha^{-1})						% increase over conventional
				IPT			Conventional			
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	
Pudukkottai: a) Annavasal										
Kothirapatti	21,800	21,800	21,800	8685	8685	8685	6154	6154	6154	25
Kattakudi	22,100	21,900	22,000	8372	8934	8653	6195	6700	6448	26
Mean	21,950	21,850	21,900	8529	8810	8669	6175	6427	6301	26
Avoor	19,800	17,000	18,400	7743	9400	8572	5730	7332	6531	25
Thennambadi	22,000	21,000	21,500	8058	8836	8447	5963	6539	6251	26
Kathalur	23,000	21,400	22,200	8342	8609	8476	6173	6371	6272	26
Mean	21,600	19,800	20,700	8048	8948	8498	5955	6747	6351	26
Tiruchirappalli: Manikandam										
Poongudi	20,000	18,000	19,000	7548	8475	8012	5585	6526	6056	25
Esanapatti	20,600	17,800	19,200	7941	8945	8443	5818	6652	6235	25
Paganur	24,000	19,000	21,500	7776	8611	8194	5754	6631	6193	25
Kallikudi	23,000	19,000	21,000	7580	9244	8412	5609	7069	6339	25
N.K.pattu	24,600	24,600	24,600	8353	8353	8353	6515	6515	6515	22
Punganur	20,000	17,600	18,800	7862	8593	8228	5975	6389	6182	25
Mean	22,033	19,333	20,683	7843	8704	8273	5876	6630	6253	25
Over all mean	21,861	20,328	21,094	8140	8821	8480	6002	6601	6302	26

Name of the block/ village	Rice fallow blackgram grain yield (kg ha^{-1})						% increase over conventional
	IPT			Conventional			
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	
Kothirapatti	730	730	730	548	548	548	25
Kattakudi	700	718	709	525	553	539	24
Mean	715	724	720	537	551	544	25
Avoor	638	730	684	480	548	514	25
Thennambadi	645	720	683	471	540	506	26
Kathalur	600	686	643	450	515	483	25
Mean	628	712	670	467	534	501	25
Poongudi	625	700	663	450	535	493	24
Esanapatti	670	708	689	503	533	518	24
Paganur	642	710	676	488	530	509	24
Kallikudi	590	716	653	443	551	497	24
N.K.pattu	700	700	700	539	539	539	24
Punganur	680	730	705	510	570	540	25

Table 3 (continued)

Name of the block/ village	Rice fallow blackgram grain yield (kg ha^{-1})						% increase over conventional
	IPT			Conventional			
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	
Mean	651	711	681	489	542	516	24
Over all mean	665	716	690	498	543	520	25

equivalent yield of 2008 kg ha^{-1} in N K pattu village of Manikandam block was noticed with rice–blackgram system. This might be due to supply of nutrients through in situ incorporation of sunhemp, higher production potential of SRI–rice fallow–blackgram along with the good market price of rice and blackgram that yielded better grain yield than conventional method. The higher rice equivalent yield indicates that the residual advantage of a sunhemp crop on the succeeding rice–blackgram besides contribution in total system productivity. These results are in conformity with finding of Sharma et al., (2008), who reported that inclusion of legume during summer/*rabi* in rice-based cropping system resulted in an increased in productivity and profitability (Shridhara et al. 2016).

Total water productivity

Among the eleven villages of Pudukkottai and Tiruchirappalli districts, the higher water productivity was observed in Punganur followed by N.K.pattu villages of Manikandam block in Tiruchirappalli district and least water productivity was recorded Kothirapatti village of Annavasal block in Pudukkottai district under IPT. The mean higher water productivity of 0.7087 kg ha^{-1} m^{-3} (Table 5) was observed under improved production techniques in GM–SRI–RFP system than conventional method (0.2512 kg ha^{-1} m^{-3}). Similar kind of improved production technology that results in improved water productivity is reported by Surendran et al. 2021).

Extension gap

The extension gap (Table 5) was higher (1105 kg ha^{-1}) in improved production techniques of green manure–system of rice intensification (SRI)–rice fallow blackgram. The results confirmed that if improved production technologies are adopted, it will subsequently change this alarming trend of galloping extension gap (Samant 2014). The new improved technologies will eventually lead to the farmers to change the attitude of the farmers avoid the use of old varieties and to adopt new variety apart from the adoption of improved production technologies. Similar results were reported by Sharma et al. (2011).

Economics

The higher mean gross return of Rs.10,200, 151,283, and 48,134 ha^{-1} of sunhemp as Green manure, rice SRI, and rice fallow blackgram was obtained, respectively (Table 6), in improved production techniques over conventional method, i.e. farmer's practice. A higher cost–benefit ratio (1.66, 4.23

Table 4 Influence on improved production techniques on green manure–SRI–rice fallow blackgram system on initial and post-harvest soil fertility status (pooled mean of 92 locations)

S. no.	Name of the block & village	No. of demo.	EC (dSm^{-1})	pH	Initial soil status (kg ha^{-1})			EC (dSm^{-1})	pH	Post-harvest soil status (kg ha^{-1})		
					N	P	K			N	P	K
Annavasal block												
1	Kothirapatti	1	0.20	8.35	145.00	22.50	250.00	0.20	8.13	156.00	26.50	262.00
2	Kattakudi	2	0.31	8.52	128.75	20.00	193.75	0.22	8.24	140.25	24.50	204.25
	Mean		0.26	8.44	136.9	21.25	221.88	0.21	8.19	148.13	25.50	233.13
Viralimalai block												
3	Avoor	20	0.25	8.49	192.35	23.41	282.00	0.19	7.96	203.53	29.71	293.53
4	Thennambadi	2	0.21	8.49	176.75	10.00	262.25	0.13	7.815	187.75	14.00	274.25
5	Kathalur	2	0.32	8.61	154.00	38.75	277.50	1.17	8.01	165.00	43.75	289.5
	Mean		0.26	8.53	174.37	24.05	273.92	0.50	7.93	185.43	29.15	285.76
Manikandam block												
6	Poongudi	11	0.23	8.49	252.77	22.50	283.64	0.36	7.87	263.77	26.30	295.18
7	Esanapatti	10	0.22	8.44	210.05	19.44	361.95	0.15	7.85	221.55	24.33	373.30
8	Paganur	11	0.26	8.61	278.90	17.05	338.86	0.16	8.13	289.80	21.32	350.59
9	Kallikudi	24	0.37	8.51	245.04	24.89	334.19	0.26	7.96	256.13	29.11	345.90
10	N K pattu	1	0.25	8.57	350.00	27.50	322.5	0.20	8.17	361.00	31.50	334.50
11	Punganur	8	0.26	8.52	198.63	29.64	398.44	0.14	8.09	209.75	34.36	410.19
Mean			0.27	8.52	255.90	23.50	339.93	0.21	8.01	267.00	27.82	351.61
Over all mean		92	0.26	8.51	212.02	23.24	300.46	0.29	8.02	223.14	27.76	312.11

Table 5 Effect of green manure–SRI–RFP demonstration on mean biomass yield, grain yield of rice and blackgram, rice equivalent yield, total water productivity and extension gap

Name of the block/ village	No. of demo	Total water consumed (mm) (GM–SRI–RFP)		Green manure	SRI Rice yield (kg ha^{-1})			Rice fallow blackgram grain yield (kg ha^{-1})		
		Conventional method	IPT	Biomass (kg. ha^{-1})	Conventional method	IPT	% increase over conventional	Conventional method	IPT	% increase over conventional
Pudukkottai										
a) Annavasal										
Kothirapatti	1	1750	1550	21,800	6154	8685	25	548	730	25
Kattakudi	2	1730	1530	22,000	6448	8653	26	539	709	24
b)Viralimalai										
Avoor	20	1696	1513	18,400	6531	8572	25	514	684	25
Thennambadi	2	1715	1535	21,500	6251	8447	26	506	683	26
Kathalur	2	1695	1530	22,200	6272	8476	26	483	643	25
Tiruchirappalli: Manikandam										
Poongudi	11	1705	1514	19,000	6056	8012	25	493	663	24
Esanapatti	10	1713	1546	19,200	6235	8443	25	518	689	24
Paganur	11	1718	1560	21,500	6193	8194	25	509	676	24
Kallikudi	24	1716	1558	21,000	6339	8412	25	497	653	24
N.K.pattu	1	1800	1650	24,600	6515	8353	22	270	350	24
Punganur	8	1734	1618	18,800	6182	8228	25	540	705	25
Mean	92	1725	1555	21,094	6302	8480	25.2	505	671	24.7

Name of the block/ village	No. of demo	Rice Equivalent yield (kg ha^{-1})		Total water productivity (kg ha^{-1} m^{-3})		Extension gap (kg ha^{-1})
		Conventional method	IPT	Conventional method	IPT	IPT
Pudukkottai						
a) Annavasal						
Kothirapatti	1	1766	2952	0.2478	0.6669	1186
Kattakudi	2	1758	2900	0.2478	0.7274	1142
b)Viralimalai						
Avoor	20	1696	2735	0.2450	0.6952	1039
Thennambadi	2	1661	2808	0.2542	0.7163	1147
Kathalur	2	1601	2722	0.2510	0.7115	1121
Tiruchirappalli: Manikandam						
Poongudi	11	1616	2666	0.2581	0.7186	1050
Esanapatti	10	1691	2763	0.2520	0.7016	1072
Paganur	11	1665	2776	0.2551	0.7100	1111
Kallikudi	24	1642	2714	0.2537	0.7168	1072
N.K.pattu	1	1053	2008	0.2589	0.7396	955
Punganur	8	1746	2783	0.2563	0.7407	1037

Table 5 (continued)

Name of the block/ village	No. of demo	Rice Equivalent yield (kg ha^{-1})		Total water productivity (kg ha^{-1} m^{-3})		Extension gap (kg ha^{-1})
		Conventional method	IPT	Conventional method	IPT	IPT
Mean	92	1661	2766	0.2512	0.7087	1105

GM: green manure, SRI: system of rice intensification; RFP: rice fallow pulses

and 2.91 of green manure–rice–blackgram, respectively) was found in improved practice due to higher net return as compared to the conventional method (0,2.87 and 2.38) attributed to more grain production. The variation in net return and benefit–cost ratio may be attributed to the improvement in the yield and variation in the price of agri-inputs and produce. This might be due to the higher productivity of rice and blackgram grains. Many earlier studies also showed that gross returns were higher in SRI (Bharathy 2005).

Lesson learned by farmers and the impact of the study

Traditionally, farmers had been employing a rice–rice–pulses cropping system, which demanded higher water and nutrient resources and suffered from inadequate irrigation and weed management practices. However, with the introduction of improved production technology (IPT) focusing on green manure–SRI–pulses, farmers gained substantial knowledge regarding the cultivation method of green manuring, particularly sunhemp, and learned effective techniques for its incorporation into the soil. Additionally, they received guidance on proper soil sample collection methods and the impact of these technologies on soil health, when the results of post-harvest soil nutrient status were shared with them (photos attached as supplementary file).

Incorporating the system of rice intensification (SRI) led to reduced input usage, such as lower seed rates and the implementation of alternate wetting and drying practices, along with nitrogen application guided by LCC assessments. Furthermore, farmers acquired extensive knowledge regarding the utilization of high-yielding blackgram varieties resistant to MYMV, along with appropriate seed rates and seed treatment procedures involving Imidacloprid, *Pseudomonas*, *Rhizobium*, and *phosphobacteria*. They also learned the application of TNAU Pulse Wonder as a foliar spray for optimal crop growth (Table 5).

Through the implementation of improved production techniques aimed at enhancing soil fertility with the incorporation of sunhemp, improved methods for rice cultivation (SRI), and the production of rice fallow blackgram, farmers have gained invaluable technical knowledge that has significantly altered their approach to adopting appropriate production technologies. According to the survey conducted across 50 hectares involving 92 farmers in the demonstration, the impact has transferred to an area of

Table 6 Effect of frontline demonstration on cost of cultivation, gross return, net return, BCR of green manure, SRI-RFP cropping system in Ponnaniyar sub-basin

Name of the village	Greenmanure					System of rice intensification							
	Biomass (kg.ha^{-1})	Gross income (Rs.ha^{-1})	COC (Rs. ha^{-1})	Net income (Rs.ha^{-1})	BCR	Gross income (Rs.ha^{-1})		Cost of cultivation (Rs. ha^{-1})		Net profit (Rs.ha^{-1})		BCR	
						IPT	Conv	IPT	Conv	IPT	Conv	IPT	Conv
Kothirapatti	21,800	10,900	6350	4550	1.72	156,326	117,245	36,000	40,000	120,326	77,245	4.34	2.93
Kattakudi	22,000	11,000	6390	4610	1.72	155,748	116,058	35,500	39,000	120,248	77,058	4.39	2.98
Avoor	18,091	9045	5300	3745	1.71	153,136	115,654	35,850	39,350	117,286	76,304	4.27	2.94
Thennambadi	19,218	9609	5200	4409	1.85	152,044	112,512	35,500	39,500	116,544	73,012	4.28	2.85
Kathalur	21,500	10,750	6200	4550	1.73	152,565	112,898	35,500	39,500	117,065	73,398	4.30	2.86
Poongudi	20,350	10,175	6150	4025	1.65	145,891	109,961	35,636	39,455	110,255	70,507	4.10	2.79
Esanapatti	19,218	9609	5700	3909	1.69	150,344	113,180	35,800	39,300	114,544	73,880	4.20	2.88
Paganur	20,160	10,080	6150	3930	1.64	147,853	110,924	35,909	39,455	111,944	71,469	4.12	2.81
Kallikudi	20,545	10,273	6200	4073	1.66	150,791	112,928	35,958	39,750	114,832	73,178	4.19	2.84
N..K. pattu	20,521	10,260	6170	4090	1.66	150,352	117,274	36,000	41,000	114,352	76,274	4.18	2.86
Punganur	21,000	10,500	6150	4350	1.71	149,060	112,503	36,000	39,750	113,060	72,753	4.14	2.83
Mean	20,400	10,200	6150	4050	1.66	151,283	113,740	35,787	39,642	115,496	74,098	4.23	2.87

Name of the village	Rice fallow blackgram							
	Gross income (Rs.ha^{-1})		Cost of cultivation (Rs.ha^{-1})		Net profit (Rs.ha^{-1})		BCR	
	IPT	Conv	IPT	Conv	IPT	Conv	IPT	Conv
Kothirapatti	51,100	38,325	16,800	15,000	34,300	23,325	3.04	2.56
Kattakudi	49,630	37,725	16,600	15,250	33,030	22,475	2.99	2.48
Avoor	47,866	36,063	16,430	15,255	31,436	20,808	2.91	2.36
Thennambadi	47,775	35,380	16,500	15,250	31,275	20,130	2.90	2.32
Kathalur	45,010	33,758	16,650	15,350	28,360	18,408	2.71	2.20
Poongudi	46,474	35,119	16,582	15,264	29,892	19,855	2.80	2.30
Esanapatti	47,943	36,237	16,500	15,230	31,443	21,007	2.91	2.38
Paganur	47,797	36,237	16,536	15,182	31,261	21,055	2.89	2.39
Kallikudi	47,305	35,898	16,583	15,246	30,722	20,652	2.85	2.35
N..pattu	49,000	37,730	16,600	15,400	32,400	22,330	2.95	2.45
Punganur	49,569	37,114	16,488	15,188	33,081	21,926	3.01	2.45
Mean	48,134	36,326	16,570	15,238	31,564	21,088	2.91	2.38

COC: cost of cultivation, BCR: benefit–cost ratio, Conv.: conventional method, IPT: improved production techniques

170 hectares, engaging 250 farmers, specifically concerning the practices of green manure–SRI–rice fallow pulses.

Many farmers expressed their initial reluctance to adopt treated seeds, maintain appropriate plant densities, and cultivate high-yielding rice varieties resistant to blast disease and MYMV in blackgram. Additionally, they were unaware of the precise quantity of spray fluid required for both growth regulators and pesticides. However, they now possess a comprehensive understanding of these technologies and their substantial impact on crop yields. As a result, they have observed reductions in water usage and seed costs, while experiencing enhanced grain yields and improved maintenance of soil fertility, thereby rendering their agricultural practices economically viable.

Conclusion

The decline in rice production in Tamil Nadu has been a concern in recent times. Addressing these challenges requires concerted efforts involving water management strategies, implementing climate-resilient agricultural practices, providing education and support to farmers regarding modern techniques, encouraging sustainable farming practices, etc. With this as background, improved production technologies were demonstrated in farmers' fields. The demonstration results showed that the prevailing farming practices among farmers can be effectively replaced by adopting the green manure–SRI–rice fallow system, especially in irrigated conditions, to attain elevated productivity per unit area and increased income. Farmers, upon receiving training about GM–SRI–rice fallow pulses, reported a remarkable 26% and 25% surge in rice and blackgram productivity, respectively, compared to the conventional method of rice–rice–pulses cultivation. Consequently, this led to a substantial increase in net income. The extension gap also has been identified and can be addressed by adopting improved production techniques, focusing on high-yielding varieties. Newly released high-yielding and disease-resistant varieties are anticipated to substantially increase production and profits. This includes the utilization of existing high-yielding rice variety TKM13 and blackgram variety VBN8. Moreover, soil physico-chemical properties and the availability of macro nutrients in the soil after the harvest were improved by the implementation of the sunhemp–SRI–rice fallow blackgram system compared to the conventional cropping system of rice–rice–rice fallow pulses. The highest soil available nitrogen, phosphorus, and potassium levels were observed with the GM–SRI–RFP system, specifically with the sunhemp–rice–blackgram cropping sequence, recording increments of 4.98%, 16.28%, and 3.73% for N, P, and K, respectively, compared to the initial soil available NPK status.

In a nutshell, integrating green manuring into the SRI method alongside pulse cultivation, farmers can experience improved yields due to enhanced soil fertility, better nutrient availability, weed control, and improved soil structure and moisture retention, leading to overall improved crop productivity and sustainability.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10333-024-00989-3.

Acknowledgements The authors are thankful to the Tamil Nadu Agricultural university, Coimbatore, and World Bank for providing support towards conducting the front line demonstrations.

Funding TNAU -World Bank.

Data availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no competing or conflicting interests.

References

Al-Khatib K, Libbey C, Boydston R (1997) Weed suppression with Brassica green manure crops in green pea. Weed Sci 45(3):439–445

Ambika S, Somasundaram G, Sundralingam K (2015) Importance of green and green leaf manures in sustainable agriculture. Popular Kheti 3(1):62–65

Babu S, Mohapatra KP, Das A, Yadav GS, Tahasildar M, Singh R, Panwar AS, Yadav V, Chandra P (2020) Designing energy-efficient, economically sustainable and environmentally safe cropping system for the rainfed maize–fallow land of the Eastern Himalayas. Sci Total Environ 722:137874

Balasubramaniyan P, (2004) Yield potential of fine-grain rice (*Oryza sativa*) under integrated nutrient management. Indian J Agron 49(3):157–159

Banik GPK, Sasmal TK, Bhattacharya S, Sarkar BK, Bagchi DK (2006) Effect of organic and inorganic nutrients for soil quality conservation and yield of rainfed low land rice in sub-tropical plateau region. J Agron Crop Sci 192(5):331–343

Bharathy VE (2005) Effect of FYM and rotary weeding on crop yield in the system ofrice intensification (SRI) Thesis. Ranga Agricultural University, Hyderabad, India, Acharya N.G

Biwal S, Behera PK, Nayak L (2014) Effect of stated principles of SRI on the performance of *kharif* rice. In: National Symposium on Management options for enhancing farm productivity and livelihood security under changing climate, Odisha chapter, ISA, October pp 29–31

Boparai BS, Singh Y, Sharma BD (1992) Effect of green manuring with *Sesbania aculeata* on physical properties of soil and on growth of wheat in rice-wheat and maize-wheat cropping systems in a semiarid region of India. Arid Land Res Manag 6(2):135–143

Boydston RA, Hang A (1995) Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*). Weed Technol 9:669–675

Bumaya AH, Naylor DV (1988) Phosphorus sorption and extractability in andic soil incubated with plant residues of variable P content. Plant Soil 112(1):77–81

Bunch R (2012) Restoring the soil. A guide for using green manure/cover crops to improve the food security of smallholder farmers. Canadian Foodgrains Bank. Winnipeg, Canada

Chimouriya S, Lamichhane J, Gauchan DP (2018) Green manure for restoring and improving the soil nutrients quality. Int J Res 5(20):1064–1074

Choi B, Ohe M, Harada J, Daimon H (2008) Role of belowground parts of green manure legumes, *Crotalaria spectabilis*and *Sesbania rostrata*, in N uptake by the succeeding tender green mustard plant. Plant Prod Sci 11(1):116–123

CRRI (2006) Annual report, (2005–06). Central rice research institute, Cuttack56–62

Dickmann KH, Ottow JC, Diekmann KH, De Datta SK (1996) Yield and nitrogen response of lowland rice (*Oryza sativa* L.) to *Sesbania rostrata* and *Aeschynomeneafraspera* green manure in different marginally productive soils in the Philippines. Biol Fertil Soils 21(1–2):103–108

Dubey L, Dubey M, Jain P (2015) Role of green manuring in organic farming. Plant Arch 15(1):23–26

Easterwood GW, Sartain JB (1990) Clover residue effectiveness in reducing orthophosphate sorption on ferric hydroxide coated soil. Soil Sci Soc Am J 54:1345–1350

Fageria NK (2007) Green manuring in crop production. J Plant Nutr 30(5):691–719

FAOSTAT (2021) https://www.fao.org/faostat/en/#home accessed during Jan 2023

Florentín MA, Peñalva M, Calegari A, Derpsch R, McDonald MJ (2010) Green manure/cover crops and crop rotation in conservation agriculture on small farms. Integr Crop Manag 12:7

Ghosh RK, Sharma L, Barman S, Dolai AK (2009) System of rice Intensification: the alternate approach for increasing production of field crops. J Crop Weed 5:63–67

Gupta AK, Sharma RS (1991) Effect of plant spacing and fertility level on grain yield of early medium indica rice (*Oriza sativa*). Indian Journal of Agronomy 36:223–225

Hossain MZ, Hossain SMA, Anwar MP, Sarkar MA, Mamun AA (2003) Performance of BRRI Dhan 32 in SRI and conventional methods and their technology mixes. Pak J Agron 2(4):195–200

Jackson ML (1973) Soil Chemical analysis, 498. New Delhi: Prentice Hall India Pvt.Ltd.

Kafkaf U, Bar-Yosef B, Rosenberg R, Sposito G (1988) Phosphorus adsorption by kaolinite and montmorillonite II organic anion competition. Soil Sci Soc Am J 52:1585–1589

Kharub AS, Chander S (2008) Effect of organic farming on yield, quality and soil-fertility status under basmatirice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. Indian Journal of Agronomy 53(3):172–177

Kumar R, Srivastava S, Srivastava M, Sinha A (2010) Effects of organic amendments on soil mycoflora. Asian J Plant Path 4(2):73–81

Kumar R, Mahajan G, Srivastava S, Sinha A (2014) Green manuring: a boon for sustainable agriculture and pest management—a review. Agric Rev 35(3):196–206

Kumar V, Power K (2018) A review on soil health and fertility management in organic agriculture through green manuring. J Pharmacogn Phytochem 7(1S):3213–3217

Maiti S, Narzari N, Pal S (2003) Response of high yielding and hybrid rice to varied level of nutrition. Environ Ecol 21:296–300

Mishra JS, Poonia SP, Kumar R, Dubey R, Kumar V, Mondal S, Dwivedi SK, Rao KK, Kumar R, Tamta M, Verma M, Saurabh K, Santosh Kumar BP, Bhatt Malik RK, McDonald A, Bhaskar S (2021) An impact of agronomic practices of sustainable rice-wheat crop intensification on food security, economic adaptability, and environmental mitigation across eastern indo-gangetic plains. Field Crop Res 267:108164. https://doi.org/10.1016/j.fcr.2021.108164

Mondal MMA, Isla AFMS, Siddique MA (2005) Performance of 11 modern transplant *aman*cultivar in the northern region of Bangladesh. Bangladesh J Crop Sci 16:23–29

Mukundam B, Yakadri M, Raja V, Srividya S (2012) Diversification of rice (*Oryza sativa*) based cropping system for improving productivity and income in Telangana region of Andhra Pradesh. Indian J Agron 57(1):20–23

Nagarajah S, Neue HU, Alberto MCR (1989) Effect of Sesbania, Azolla and rice straw incorporation on the kinetics of NH 4, K, Fe, Mn, Zn and P in some flooded rice soils. Plant Soil 116(1):37–48

Ntakirutimana L, Li F, Huang X, Wang S, Yin C (2019) Green manure planting incentive measures of local authorities and farmers' perceptions of the utilization of rotation fallow for sustainable agriculture in Guangxi China. Sustainability 11(10):2723

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soil by extraction with sodium carbonate939. US Department of Agriculture, Washington DC

Pareek N, Yadav BL (2011) Effect of organic manures on soil physic-chemical properties, soil microbial biomass and yield of mustard under irrigation of different residual sodium carbonate waters. J Indian Soc Soil Sci 59(4):336–342

Porpavai S, Devasenapathy S, Siddeswaran K, Jayaraj T (2011) Impact of various rice based cropping systems on soil fertility. J Cereals Oilseeds 2(3):43–46

Samant TK (2014) Evaluation of front line demonstration on rice (Manaswini). Agric Update 9(3):311–315

Samant TK (2015) Impact of front line demonstration on yield and economics of hybrid rice (Rajalaxmi). Indian J Agric Res 49(1):88–91. https://doi.org/10.5958/0976-058X.2015.00013.X

Samui SK, Maitra S, Roy DK, Mondal AK, Saha D (2000) Evaluation onfront line demonstration on groundnut (*Arachis hypogea* L.). J Indian Soc Agric Res 18:180–183

Saria AG, Sibuga KP, Semu E, Jensen HH (2018) Soil fertility dynamics of ultisol as influenced by greengram and mucuna green manures. J Plant Sci Agric Res 2(2):14

Schröder J (2005) Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Bioresour Technol 96(2):253–261

Senthilvalavan P, Ravichandran M (2020) Post harvest soil fertility status of rice-blackgram cropping system In*typic haplustertsin*-fluenced by integrated nutrient Management and crop cultivation techniques. Plant Archives 20(1):2644–2649

Shan H, Yongjun Z, Jianfu W, Qinghua S, Xiaohua P (2013) Effect of crop residue retention on rice yield in China: A meta-analysis, Field Crops Research, Volume 154, 188–194, ISSN 0378–4290,https://doi.org/10.1016/j.fcr.2013.08.013. (https://www.sciencedirect.com/science/article/pii/S0378429013002931)

Sharma RP, Pathak SK, Haque M, Lal M (2008) Productivity, profitability and nutrient balance as influenced by diversification of rice (*Oryza sativa*) - wheat (*Triticum aestivum*) cropping system. Indian J Agron 53(2):97–101

Sharma P, Khar S, Kumar S, Ishar A, Prakash S, Mahajan V, Jamwal S (2011) Economic impact of front line demonstrations on cereals in Poonch district of Jammu and Kashmir. J Progress Agric 2:21–25

Shridhara B, Nagoli MA, Basavanneppa Gl, Sawargaonkar DP, Biradar SA, Birada MR, Navyashree (2016) Soil fertility as influenced by alternate sequential cropping systems to rice-rice (*Oryza sativa* L.) In Tunga Bhadra project area. Eco Env Cons 22 (April Suppl): S445-S448

Singh Y, Khind CS, Singh B (1992) Efficient management of leguminous green manures in wetland rice. Adv Agron 45:135–189

Singh BB, Jones JP (1976) Phosphorus sorption and desorption characteristics of soil as affected by organic residues. Soil Sci Soc Am J 40:389–394

Sinha A, Kumar R, Kamil D, Kapur P (2009) Release of nitrogen, phosphorus and potassium from decomposing *Crotalaria juncea* L. in relation to different climatic factors. Environ Ecol 27(4B):2077–2081

Sruthi P, Surendran U (2023) Evaluation of nutrient management and method of planting on crop productivity of aerobic rice and estimating the water saving in aerobic using FAO-CROPWAT model. Paddy Water Environ 21:467–477. https://doi.org/10.1007/s10333-023-00941-x

Subbiah BV, Asija GL (1956) A rapid procedure for estimation of available nitrogen in soil. Curr Sci 25:259–260

Sudhakar P, Kuppuswamy G (2007) Evaluation of different organic manures in rice and their impact of succeeding crops. Plant Arch 7(1):439–441

Sudhakar PC, Singh JP, Yogeshwar S, Singh R (2006) Effect of graded fertility levels and siliconsources on crop yield, uptake and nutrient-use efficiency in rice *(Oryza sativa)*. Indian J Agron 51(3):186–188

Surendran U, Rama Subramoniam S, Raja P (2016) Budgeting of major nutrients and the mitigation options for nutrient mining in semi-arid tropical agro-ecosystem of Tamil Nadu India using NUTMON model. Environ Monit Assess 188:250. https://doi.org/10.1007/s10661-016-5202-x

Surendran U, Raja P, Jayakumar M, Subramoniam SR (2021) Use of efficient water saving techniques for production of rice in India under climate change scenario: a critical review. J Clean 309:127272

Verma SP, Mudgal SC (1983) Production potential and economics of fertilizer application as a resource constraints in maize-wheat crop sequences. Himachal J Agril Res 9(2):89–92

Wang S, Cao W, Jiang D, Dai T, Zhu Y (2003) Effect of SRI technique on physiological characteristics and population development in rice. Chin J Rice Sci 17(1):31–36

White RE, Ayoub AT (1983) Decomposition of plant residues of variable C/P ratio and the effect on soil phosphate availability. Plant Soil 74:163–173

Yang J, Zhou Q, Zhang J (2018) Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission. Crop J 5(2):151–158