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A Best-Bet System of Rice Intensification for Sustainable Rice (*Oryza sativa* L.) Production in Northwestern Nigeria

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Abstract: System of Rice Intensification (SRI) practices are expected to be used in location-specific ways and thus will vary somewhat across countries and regions. This study undertook to identify a 'best-bet' version of SRI for conditions in northwestern Nigeria, considering what is feasible for farmer use. Two years of experimental data from 260 farmer-managed rice plots evaluating four of the SRI practices in Zamfara State were analyzed. The variables evaluated were seedling age at transplanting, plant density, irrigation schedule, and fertilizer application. Farm budget analysis showed that the best-bet SRI practices most productive given the natural environment and farming system were transplanting 11-day-old seedlings at 25 cm × 25 cm spacing, with alternate wetting-and-drying of fields, as well as providing full compost plus some inorganic fertilization. Net economic returns were found to be highest with best-bet SRI practices and ranged from USD 1450–2120 ha^{-1}. While rice production was profitable under both SRI and more conventional management, the return on investment was at least 40% higher with SRI practices than with the other practices evaluated. Based on our data and analysis, we recommend that the Nigerian government and its development partners prioritize and expand the testing and promotion of SRI in the northwest and other regions of the country. This initiative can significantly enhance farmers' incomes and, ultimately, bolster food security.

Keywords: rice production; System of Rice Intensification; fertilizer application; return on investment

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1. Introduction

Nigeria still has a large and serious deficit in rice production despite significant improvement in its domestic production in recent years. The shortfall is due to a number of factors including continuing population growth, low agronomic productivity, high cost of inputs, climate change, and various political and other conflicts. At present, the population in Nigeria consumes between 7.3–7.5 million tons of rice annually [1–4], while Nigerian farmers are producing about 4–5 million tons per annum [3,4], leaving a gap of 2.9–3.5 tons to be filled by imports or domestic production. Considering that milled (edible) rice is lower in volume than paddy rice, farmers' production in Nigeria of the latter needs to double or more, even as many households are changing their food consumption patterns to cheaper alternatives, especially from rice to maize, cassava, or yam [5] as the population continues to increase.

There is considerable scope for raising rice production because the current national average yield is less than 2 tons of paddy rice per hectare, while the average yield in West Africa is 2.6 tons [6]. Lowland irrigated rice production in northern Nigeria has the potential to yield between 6 and 10 tons of paddy rice per hectare with improved varieties and with good farm practices [4], but irrigated land is limited, so it is important to get the best yields possible on whatever irrigated paddy land is available. At present, the actual yield in northern Nigeria, even with irrigation, is between 2–3 tons of paddy rice per hectare [6].

The System of Rice Intensification (SRI) is reported to be a climate-smart agriculture that could address the rice shortfall in the country with environmental, economic, and social benefits to both small and large-scale farmers [7,8]. An evaluation in eastern Indonesia of the results from over 12,000 on-farm comparison trials across eight districts reported an average yield increase of 78% with SRI (3.3 t ha^{-1}), using 40% less water and with 20% lower costs of production per hectare [9]. In the Andhra Pradesh state of India, a detailed study by [7] covering many aspects of rice system performance reported that SRI provided farmers with both economic and environmental benefits, raising their average paddy yield by 60% while reducing their groundwater use by 60% and fossil fuel consumption by 74%. Greenhouse gas emissions were reduced by 40% per ha and by 60% per kg of rice produced.

The Federal Government of Nigeria, represented by the Federal Ministry of Water Resources (FMWR), has been implementing, with World Bank assistance, a seven-year project (Transforming Irrigation Management in Nigeria, TRIMING) with the aim of achieving sustainable growth in food production and agricultural productivity. The project, started in 2014, focused on five irrigation schemes located in three river basins in northern Nigeria. These included the Bakolori Irrigation Scheme where a sizeable portion of farmland is used for rice cultivation in both the dry and rainy seasons.

The Institute for Agricultural Research (IAR) at Ahmadu Bello University in Kaduna State was engaged to carry out research on the testing and promotion of SRI practices for sustainable rice production in the Bakolori scheme, including appropriate tools and machineries. In collaboration with the Agricultural Extension Research and Liaison Services and the National Centre for Agricultural Mechanization, the TRIMING-SRI project was carried out in three years starting from March 2018 through 2020. Within the project's first two years (2018 and 2019), SRI practices and small-scale, economically viable tools and machinery were tested and evaluated to identify the best-bet SRI practices suitable for the project area.

Despite the positive SRI results reported in the published literature, however, there is still not widespread acceptance of its appropriateness for rice production in Nigeria. Under the TRIMING project, a systematic effort was made to identify what would be the most appropriate SRI practices that could enable farmers to increase their rice yields and incomes with relatively little capital expenditure. This study thus addresses the debate surrounding the value of SRI as a strategy for improving farmers' livelihoods and national food security in an environmentally friendly way.

It was recognized that SRI is not a fixed set of practices to be applied the same everywhere, so an effort was made to identify what would be the most productive practices under the particular climatic, soil, and other conditions of the Bakolori irrigation scheme in Zamfara state. What should be presented to farmers as 'best-bet SRI' in a location where there was enough water control so that the soil could be kept moist but not flooded during the cropping season? To determine this, this project supported a multi-year field study with farmer participation, engaging agriculture faculty and students from the Ahmadu Bello University in Zaria, Nigeria to assist in monitoring and in data gathering and evaluation.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Bakolori Irrigation Scheme (BIS) located in Zamfara State, northwestern Nigeria, in three of its fourteen Local Government Areas (LGAs): Talata Mafara, Maradun, and Bakura [10]. The Bakolori dam whose water supplies the project site had a water storage capacity of 450 million cubic meters at the time that its construction was completed in 1979, but 34 years later, this was estimated to be 350 million cubic meters.

The dam presently supplies water to 23,000 ha in the BIS, of which 7039 ha (31%) are served by gravity, and 15,961 ha (69%) through sprinklers.

The climate in the study area is dominated by a single rainy period, ranging from 500 to 1300 mm, with intermittent storms from June to September. The average air temperature is 30 °C with a peak at 35 °C between March and May. The main soil types in the area range from sandy loam to loamy sand, classified as Typic Haplustalf according to USDA classification, or as Haplic Luvisols/Lixisols in FAO-UNESCO nomenclature. Their pH varies between 5.4 and 6, making them moderate to slightly acidic [11]. These soils are dominant on the slopes, while the floodplains in the area are predominantly black soils, originally lateritic with abundant iron; this element has become reduced rather than oxidized. Organic matter was high in some sectors, while it was moderate to low in others. Available phosphorus and exchangeable potassium are both low across the sectors. More than 80% of the cultivated irrigated area in this region is used for growing rice.

2.2. Experimental Design

The TRIMING-SRI project was implemented in two phases. The first was the testing of SRI practices during two rice farming seasons, in 2018 and 2019, while the second was promotional research carried out in 2020. This paper reports on the first phase of the project, which started with farmers' field schools (FFS), in which 25 farmers from each of the seven sectors within the study area participated. In 2018, SRI practices were tested on three to five farmers' fields in each of the seven sectors and were compared with farmers' current practices. Then, in 2019, in an effort to determine the optimum value for each of the respective SRI practices assessed, trials were conducted with five farmers attached to each trial field. In all, there were 260 SRI plots.

While all the SRI practices were utilized on the first-year trial plots, four were evaluated in a *ceteris paribus* way in the second year to determine what specific practices were most suitable for the prevailing situation in the Bakolori system to maximize productivity. The four practices were seedling age at transplanting (SAT); spacing distance and pattern; irrigation regime (flooding vs. alternate wetting and drying); and fertilizer use. These practices were evaluated with a factorial research design that permitted us to consider each.

The distribution of the SRI trial plots, each 60 m^2, within the Bakolori system is shown in Table 1. For each plot with an SRI treatment, a conventionally managed plot managed by the farmers nearby, one that had similar soil characteristics, was selected and evaluated for making comparisons between SRI and existing farming methods. The total number of plots evaluated in this study was thus 520, i.e., 260 plots with SRI treatments, plus another 260 plots managed with farmer practice (FP).

Table 1. Number of rice plots in BIS managed in 2018 and 2019 in each of the seven sectors for testing of SRI practices.

Practices	Year	M-Rice B	North Central	N-Rice	E-Right up	E-Left	G-Rice B	F-Left	Total
Spacing pattern	2018	5	5	5	5	4	5	5	34
	2019	5	7	5	7	5	6	5	40
Seedling age	2018	5	4	3	0	0	0	0	12
	2019	7	5	3	5	8	5	7	40
Water mgmt.	2018	5	3	5	3	3	5	4	28
	2019	5	6	7	3	6	8	5	40
Fertilizer trials	2018	5	3	3	5	3	3	4	26
	2019	0	6	4	7	10	13	0	40
Sample totals	2018	20	15	16	13	9	15	12	100
	2019	17	24	19	22	29	32	17	160
	Total	37	39	35	35	38	47	29	260

The rice variety used in all the trials except for farmers' practice (FP) was Faro 44, an improved semi-dwarf variety, known for lodging resistance and high yield. In the FP trial plots, farmers were free to choose whatever variety they thought would give them the highest yield. Most planted their preferred improved variety, as local varieties have gone out of favor.

2.3. Treatment Interventions

Generally, the recommendations for SRI are the following:

- Transplanting seedlings at wider spacing (lower plant density) with a range of spacing, from 25 cm × 25 cm up to 50 cm × 50 cm (row-to-row and plant-to-plant); the widest spacing is only for the most fertile soils, which are rare in northern Nigeria.
- Transplanting younger seedlings of 8–14 days of age (2–3 leaf stage).
- Alternate wetting-and-drying irrigation (AWD) instead of continuous flooding.
- Additionally, providing appropriate rate of compost and farmyard manure (FYM) with NPK possibly added.
- Note that the SRI recommendation of mechanical weeding was not included in this evaluation because farmers considered it to be too costly. Moreover, such weeders are not easily available in the area. So, manual weeding was done in these trials instead.

The first phase of the research sought to determine in general what would be the preferable age for transplanting young seedlings, spacing between plants, irrigation method, and fertilizer regime to recommend to farmers in the study area in northwestern Nigeria. The second phase was designed to identify what would be an optimizing combination of SRI practices to recommend, and what combination would be most suitable in our study area for greatest productivity and profitability. The participating farmers were involved in all the stages of the trials, from nursery establishment through land preparation, water and nutrient management, pest and weed control, soil and plant sampling, up to harvest and threshing.

As noted above, for the sake of optimization, four different treatments were evaluated in the second-year SRI trial fields. In the first set SRI fields, seedling age was assessed while all the other SRI practices were kept constant. Seedlings of different ages were transplanted at 9 days, 11 days, 13 days, or 14 days. At the same time, in the non-SRI plots, seedlings aged 16 days and 18 days and even older (farmers' practices can exceed even 30 days) were transplanted. In the second set of SRI plots, while all other practices were kept constant, the spacings of 25 cm × 25 cm and 30 cm × 30 cm were compared, while on the non-SRI plots, transplanting was done with 20 cm × 20 cm distance between plants, or with farmers' random close spacing.

In the third set of SRI plots, AWD was used as the irrigation method for all of these, while all of the non-SRI plots were kept continuously flooded. The AWD irrigation regime involved applying 2.5 cm of standing water on the soil surface, allowing the water to seep into the soil. To determine the soil–water level in the soil, an observation well was installed in the field. When the water level fell below 15 cm, the next AWD cycle was carried out. For continuous flooding, the field was flooded with 5–6 cm depth of water, and when the level of water dropped close to the soil surface, the field was flooded again with water.

Finally, the fourth set of SRI plots in the second year evaluated different rates and kinds of fertilization used with other SRI methods. Four treatments and two controls were considered on the respective sets of SRI and non-SRI plots: (1) recommended full rate of NPK (100 kg N urea, 50 kg P_2O_5, and 40 kg K_2O); (2) 75% of the recommended rate of NPK, together with a full recommended rate of compost (5 tonnes ha^{-1}); (3) 50% of the full rate of NPK, and 50% of the recommended rate of compost; (4) full dose of organic fertilizer (5 tonnes of compost ha^{-1}); (5) absolute control, application of neither chemical nor organic fertilizer; and (6) farmers' current fertilizer application rate which was calculated from farmer information as 120 kg ha^{-1} of urea, 90 kg ha^{-1} of NPK, and 2400 kg ha^{-1} of manure. Note that seedlings were transplanted in such a manner that the population density was 160,000 plants ha^{-1} in the first, third, and fourth set of plots.

2.4. Data Collection and Analysis

The study collected primary data from the participating rice farmers using structured, pre-tested questionnaires that were administered to them and field assistants by trained extension agents in 2018 and 2019. The researchers who supervised the plot trials were interviewed, and detailed data on input costs were collected to cross-check the data supplied by farmers. Moreover, relevant information received from focus group discussions with both farmers and extension agents who were regularly in the field was also considered for interpretation of the results. The data were analyzed using descriptive statistics and standard farm budget techniques.

3. Results

3.1. Costs for and Returns from Seedling Age at Transplanting

Table 2 reports the costs and returns of rice production based on differences in seedling age at transplanting. The SRI plots had seedlings that were 9, 11, 13, or 14 days old (DOS) while non-SRI plots had seedling with ages of 16 or 18 DOS or farmers' practice. The latter were considered as the control for purposes of comparison. The costs of production with 9-, 11-, 13- or 14-day-old seedlings (DOS) did not vary significantly, averaging USD 559 ha^{-1}. On the other hand, the total cost of production for farmers' practices was 6% higher; USD 592 ha^{-1}, while with 16 and 18 DOS, the costs of production were slightly lower, USD 542 ha^{-1}, a difference of 3%, which is not statistically significant and is attributable to small differences in inputs for the different combinations of practices, e.g., seed where spacings differed.

Table 2. Costs and returns of rice production by transplanting seedlings of various ages with SRI vs. non-SRI methods, averages for two years, 2018 and 2019 (reported in 000 Naira ha^{-1}).

	SRI				Non-SRI			Change (%)			*t*-Test
Variable	**9 DOS**	**11 DOS**	**13 DOS**	**14 DOS**	**16 DOS**	**18 DOS**	**FP**	**SRI vs. 16 DOS**	**SRI vs. 18 DOS**	**SRI Vs. FP**	**SRI vs FP**
Cost of land cultivated	35	35	35	35	35	35	35	0	0	0	NA
Cost of seed used	0.75	0.75	0.75	0.75	0.75	0.75	2.3	0	0	(−97)	10.9 ***
Cost of fertilizer	44	44	44	44	44	44	75	0	0	(−41)	10.9 ***
Cost of labor used [a]	123	123	123	122	120	121	101	2–3	1–2	21–22	−15.3 ***
Cost of chemicals	5.75	5.75	5.75	5.75	5.75	5.75	3.5	0	0	64	10.9 ***
Cost of empty bags [b]	14	15	14	13	12	12	8	6–17	10–21	37–43	−22.6 ***
Total production costs	249	251	248	247	240	243	263	3–5	2–4	(−6)–(−5)	−0.34
Yield (1000 kg ha^{-1})	9.52	10.15	9.26	9.14	8.64	8.21	5.39	6–18	11–24	69–88	−21.6 ***
Revenue ha^{-1}	1003	1070	975	960	905	859	567	6–18	12–24	69–89	−21.6 ***
Net return ha^{-1}	754	818	727	712	665	617	304	7–23	16–33	134–169	−20.8 ***
Return on investment	3.02	3.25	2.93	2.88	2.77	2.54	1.16	4–17	13–28	148–180	−18.3 ***

'Change' here represents the gain or loss between using SRI or non-SRI methods; *t*-test = difference between average of SRI and farmers' practices; *** < 0.01; NA = not available or not applicable. [a] Cost of land preparation, weeding, fertilizer application, bird scaring, harvesting, threshing, and bagging; [b] Bags purchased to bag harvested rice. At the time that the survey was conducted, USD 1.00 was equivalent to NGN 445.

For farmers' practices, 132 kg of rice seeds were used ha^{-1} and 2.4 t of FYM ha^{-1}. This means that for every 1 kg of inorganic fertilizer used ha^{-1} on SRI plots, 26.4 kg ha^{-1} of fertilizer were applied on farmers' conventionally managed fields. Conversely, for every 2.1 t of organic fertilizer ha^{-1} used with SRI, only 1 t ha$-^{1}$ was used with farmers' practices, i.e., 50% less. This had direct implications for the costs of production. The cost of labor for planting with 16 and 18 DOS was hardly different from the cost incurred with transplanting SRI's younger seedlings, but it was 18% lower than with farmers' practices, where several times more seedlings are planted, although with less care.

The effect of SRI management on farmers' labor requirements for rice cultivation depends in large part on how labor-intensive a farmer's current practices are, and on how experienced and confident the farmer is when using the new methods. In the Mwea Irrigation Scheme in Kenya, a survey of 50 farmers who had used SRI methods showed a similar average increase of 8% in their labor requirements with the new methods. However, in three of the ten units covered by the survey, farmers reported that with SRI, the amount of labor that they needed per hectare was 13% less on average [12].

How SRI affects farmers' labor requirements will also depend on how much the SRI operations for crop establishment and weeding are mechanized or motorized. In most of Asia, where rice production is quite labor-intensive at present, SRI methods have usually been found to be labor-saving, or at least labor-neutral [9]. In most of Africa, we can expect that SRI management will increase farmers' labor inputs, at least initially, because their current methods of rice production are not as labor-intensive as in Asia. This is something that the TRIMING project addressed, recognizing that mechanization for SRI will have a big impact on the acceptability and spread of the new methods in Africa.

There was significant cost saving for seeds (97%) and fertilizer (41%) with SRI vs. farmers' practices, which could be associated with the constant problem of pests in the study area. The higher cost of chemicals under SRI-based management was unexpected because the irrigation regime adopted under SRI is anticipated to mitigate the proliferation of pests and diseases [13]. We are not sure why there was more expenditure for this. Transitioning from conventional rice farming to SRI practices can require adjustments and learning for farmers. During the initial phase, farmers may still be experimenting with new techniques and facing challenges in pest and disease management. This learning curve could result in increased chemical usage until farmers become proficient in the integrated pest management (IPM) techniques specific to SRI.

The cost of land and water was at a fixed rate for all of the SRI and non-SRI trials, although it varied somewhat between the two years, NGN 37,000 ha^{-1} (USD 83) in 2018 and NGN 33,615 ha^{-1} (USD 76) in 2019, perhaps due to increased demand for arable land. There were some greater costs for SRI methods associated with having a larger harvest (transport costs were 74–89% more, and bags for storage 37–43% more).

The land productivity using SRI methods averaged 9.5 t ha^{-1}, which was 28% higher than with non-SRI methods and 76% higher than with current farmers' practices. Transplanting 11 DOS was overall the most productive seedling-age treatment, exceeding the average yields for other SRI and non-SRI treatments by 7% and 89%, respectively. This finding is similar to other studies that have found that SRI treatments with 12 DOS were more productive than with older or younger seedlings [14,15].

The yield difference significantly increased when moving to SRI with younger compared to older seedlings. Specifically, the yield differences between SRI with young seedlings vs. SRI with 16 DOS ranged from 6–18%, and from 12–24% vis-a-vis SRI with 18 DOS. The difference was much greater (69–89%) when comparing SRI with young seedlings vs. farmers' practices where seedlings are transplanted usually after at least a month in the nursery. This confirmed that planting seedlings at a younger age than present practice has a positive and significant influence on rice yield, and 11 DOS was the optimal in these trials.

The data also indicated that planting single seedlings in a square grid pattern improved yield over current practice. The positive yield effect of transplanting younger seedlings can be attributed in part to the fact that SRI transplanting is done more carefully. With careful uprooting from the nursery and quick transport to the field, there is little root trauma, effectively establishing the rice plants and minimizing 'transplant shock'.

The average net return per hectare for treatments that used 9, 11, 13, or 14 DOS ranged from USD 1640 to USD 1840 ha^{-1}, averaging USD 1692 ha^{-1}. The differential in net returns increased substantially compared with transplanting older seedlings. Net returns for SRI using young seedlings were 7–23% higher than with 16 DOS; 16–33% higher than with 18 DOS; and 134–169% higher than with farmers' practices. Furthermore, with SRI the return on investment (ROI) averaged 3 Naira ha^{-1} for every Naira invested, 40% higher than the average with non-SRI practices. The treatment with 11 DOS had the highest ROI, 3.25 ha^{-1}. This was 51% higher than from the non-SRI treatments, 17% higher than with 16 DOS, 28% higher than with 18 DOS, and 180% higher than with farmers' practices.

It should be noted that current farmers' practices have a ROI that was not much more than break-even, meaning that current rice cultivation is only marginally profitable. Overall, with SRI management and younger seedlings, farmers' net return ha^{-1} was increased by 103–169% compared to using either SRI management with older seedlings, i.e., beyond the 3rd phyllochron, or farmers' current methods. Similarly, farmers' ROI ha^{-1} was greater by 119–180% with SRI management using optimally young seedlings (11 DOS).

Because SRI is considered to be more labor-intensive than conventional methods of farming, it might have been expected that there would be significant differences in the total costs of production among the respective treatments, and particularly between SRI-based treatments and farmers' practices. In our trials, however, the average expenditure on labor inputs under SRI management across the two years and the different ages of seedlings was only 8% higher. This increase in labor cost was not enough to create a significant difference in total costs between the SRI and non-SRI trials, and there were considerably higher net returns with SRI crop management because of the higher yields.

3.2. Costs and Returns of Spacing Patterns

Table 3 analyzes the costs and returns of rice production based on SRI (25 × 25 cm and 30 × 30 cm) and non-SRI (20 × 20 cm and farmers' practices) treatments in terms of spacing patterns. The 20 × 20 cm spacing pattern was a modified SRI treatment while farmers' practices were regarded as a control for comparison. Other practices that were included in each SRI and modified SRI treatment were transplanting young (14 DOS) rice seedlings singly per hill, alternate wetting-and-drying (AWD), application of the full rate of compost (5 tonnes ha^{-1}), plus half of the recommended rate of N (50 Kg ha^{-1}), full rate of P_2O_5 (50 Kg ha^{-1}), and full rate of K_2O (40 Kg ha^{-1}) as basal fertilizer (as compound NPK 15:15:15), with also an application of urea super-granule (USG) at a rate of 50 Kg ha^{-1} as top dressing.

Table 3. Costs and returns analysis of rice production by transplanting at different spacing practices per hectare, averages for two seasons, 2018 and 2019 (reported in 000 Naira ha^{-1}).

	SRI		**Non-SRI**		**Change (%)**		***t*-Test**
Variable	**25 × 25 cm**	**30 × 30 cm**	**20 × 20 cm**	**FP**	**SRI vs. 20 × 20 cm**	**SRI vs. FP**	**SRI vs. FP**
Cost of land cultivated	35.3	35.3	35.3	35.3	0	0	NA
Cost of seed used	0.8	750	0.9	22.8	(−12)–(−6)	(−97)–(−96)	12 ***
Cost of fertilizer applied	43.7	43.7	43.7	74.7	0	(−41)	12 ***
Cost of labor employed	128.2	126.4	131.2	100.1	(−4)–(−2)	26–28	−17.1 ***
Cost of chemicals applied	5.8	5.8	5.8	3.8	0	53	−12 ***
Cost of water applied	6.2	6.2	6.2	6.2	0	0	NA
Transport costs	20.6	21.6	20.5	10.2	1–5	103–112	−15 ***
Cost of empty bags	13.93	14.6	13.8	7.5	1–6	87–96	−16.2 ***
Total production costs	254.6	254.3	257.3	260.5	(−1)	(−2)	−0.6
Yield (1000 kg ha^{-1})	11.4	11.0	10.7	6.2	3–7	77–84	−27.9 ***
Revenue ha^{-1}	1197	1154	1120	656	3–7	76–83	−30 ***
Net return ha^{-1}	943	899	863	395	4–9	128–139	−26.8 ***
Return on investment	3.7	3.5	3.6	1.5	5–11	135–147	−24 ***

'Change' here represents the gain or loss between SRI and non-SRI; *t*-test = difference between SRI and FP (farmers' practices); NA = not available or not applicable; *** < 0.01. At the time the survey was conducted, USD 1 was equivalent to NGN 445.

The cost of rice production for the two-year period was practically the same for the 25 × 25 cm and 30 × 30 cm spacing patterns, averaging USD 572 ha^{-1}. The total cost for non-SRI spacing such as 20 × 20 cm spacing and farmers' practices was not statistically different, but marginally greater (2%) than the SRI-recommended spacing. We note that when large-scale factorial trial evaluations were done of SRI methods in Madagascar in 2000 and 2001, there was no significant difference found between spacing of 25 × 25 cm vs. 30 × 30 cm [16].

That the differential in total costs for the different treatments is insignificant does not give a clear picture of the observed variability in the allocation of resources across the treatments, however. There were differences between SRI and FP in terms of the cost of labor, transport, and bags used for storing and transporting paddy rice. For instance, the cost of labor for 25 × 25 cm and 30 × 30 cm spacing patterns averaged USD 286 ha^{-1}, 27% higher than for farmers' practices, and just 3% less than the 20 × 20 cm spacing pattern. As expected, there were no significant differences between 25 × 25 cm, 30 × 30 cm and 20 × 20 cm spacing patterns with respect to cost of seed, fertilizer, chemical, and water use.

The land productivity varied only slightly among the spacing patterns and across the two-year period, although there was substantial variation for farmers' practices, 6.8 t ha^{-1} in 2018, and 5.6 t ha^{-1} in 2019. The reduction of 21% in the latter year suggests that yield under farmers' practices is more sensitive to climate effects than SRI. This could also be due to farmers using varieties that responded differently to environmental conditions, affecting land productivity. The yield for the 25 × 25 cm and 30 × 30 cm spacing patterns averaged 11.2 t ha^{-1}, which was 5% higher than with 20 × 20 cm spacing and 81% higher than with farmers' practices.

The treatment with 25 × 25 cm spacing had the highest net return, averaging USD 2118 ha^{-1}, respectively, 5% and 9% higher than with 30 × 30 cm and 20 × 20 cm spacing. The difference in net return compared with farmers' practices was very great, as the latter returns were 140% less. With SRI, the principle is to optimize spacing between plants so that each plant can give maximum expression to its genetic potential. Because rice plants are usually planted quite close to one another, this means that wider spacing will usually be closer to an optimum. However, depending on the fertility and functioning of the soil, there will be some wider distance beyond which soil and solar resources are not fully utilized, and yield will decline compared to that with closer plant spacing.

The difference in ROI between 25 × 25 cm spacing and farmers' practices was similarly the greatest of all the pairwise comparisons among the treatments. Specifically, for every USD 1 invested, USD 3.7 ha^{-1} was returned with 25 × 25 cm spacing, 147% more than with farmers' practices. Compared with 30 × 30 cm and 20 × 20 cm spacing, 25 × 25 cm spacing was just 5% and 11% higher, respectively.

An inter-plant distance of 25 × 25 cm was the most productive and profitable spacing under SRI. This could result from the wider spacing reducing root competition, also enhancing tillering and enabling plants to have more vigorous growth [14], optimally utilizing available sunlight and soil nutrients. According to [16], spacing patterns within a range between 25 × 25 cm and 50 × 50 cm can optimize SRI plants' density depending on soil fertility, rice variety, and other factors.

It is reported by [16] that 25 × 25 cm and 30 × 30 cm spacing had significantly higher numbers of tillers per plant than more closely spaced or more widely spaced plants. Varying yield effects from spacing have been reported in previous studies [14]. However, in general, our finding agrees with that of [17] which reported an average yield increase of 20–50% or more with SRI in the Tamil Nadu state of India. Rice production in the Bakolori Irrigation System using both SRI and non-SRI spacing practices was profitable, with the profitability of the SRI-based spacing patterns significantly higher than those with non-SRI spacing. Although rice production using FP was somewhat less costly ha^{-1}, 25 × 25 cm spacing proved to be the most productive and profitable.

3.3. Costs and Returns of Irrigation Regimes

Table 4 analyzes the costs and returns of rice production based on SRI (SRI/AWD) and non-SRI (SRI/flooded) treatments where SRI/flooded is actually a modified SRI treatment. Practices that were included in both SRI and modified SRI treatments were transplanting young (14 DOS) rice seedlings, singly per hill at the spacing of 25 × 25 cm, with application of a full rate of compost (5 tonnes ha^{-1}) plus half of the recommended rate of N (50 Kg ha^{-1}), full rate of P_2O_5 (50 Kg ha^{-1}), and full rate of K_2O (40 Kg ha^{-1}) as basal fertilizer in the form of compound NPK (15:15:15), also with application of urea super-granules (USG) at the rate of 50 Kg ha^{-1} as top dressing.

Table 4. Costs and returns analysis of rice production under alternative irrigation practices per hectare, average for two seasons, 2018 and 2019 (reported in Naira ha^{-1}).

Variable	SRI/AWD	SRI/CF	Change (%)
Total cost of rice production	248.6	256	−3
Yield (1000 kg ha^{-1})	10.5	4.6	128
Revenue ha^{-1}	1100.4	481.6	129
Net return ha^{-1}	851.7	225.4	278
Return on investment	3.4	0.9	280

AWD = alternate wetting and drying; CF = continuous flooding. 'Change' represents the % gain or loss between SRI and CF. The values in the table are expressed in Nigerian naira (NGN) so that the comparison is based on the local context and changes in the exchange rate would not affect the comparison between SRI with alternate wetting and drying irrigation (SRI/AWD) and with continuous flooding (SRI/CF). At the time the survey was conducted, USD1 was equivalent to NGN 445.

There were some variations in the allocation of resources within both management practices that affected their respective costs of production. On average, the cost of fertilizer and water for SRI with AWD was practically 40% less than with farmers' practices. For every USD 1 ha^{-1} spent on seed for SRI with AWD, USD 26 were spent for farmers' practices, as SRI reduced seed costs by 97%. On the other hand, with farmers' practices, there was a 25% lower cost for labor, 53% less spent for chemicals, 155% less for transport, and 133% less for bags, the latter two effects attributable to the lower yields with current methods.

The total cost of rice production under SRI/AWD was USD 559 ha^{-1}, while it amounted to USD 575 ha^{-1} under SRI/CF, indicating a 3% decrease in favor of SRI/AWD. In terms of yield, SRI/AWD resulted in a significantly higher output, 10.5 t ha^{-1} compared to 4.6 t ha^{-1} with SRI/CF, representing a 128% advantage for SRI/AWD. Consequently, the revenue generated per hectare using SRI/AWD was USD 2473, substantially higher than the revenue of USD 1082 ha^{-1} obtained from SRI/CF, a 129% advantage in favor of SRI/AWD. Moreover, SRI/AWD demonstrated a much higher net return at USD 1914 ha^{-1}, in comparison to SRI/CF's net return of USD 225 ha^{-1}, an impressive 278% advantage for SRI/AWD. The return on investment with SRI/AWD was 3.4, while it was only 0.9 for SRI/CF. These differentials could in part be due to the difficulty that young seedlings would have in getting established under flooded conditions.

3.4. Costs and Returns under Different Fertilizer Regimes

Table 5 evaluates the costs and returns of rice production based on SRI methods with full compost; $\frac{1}{2}$ compost and $\frac{1}{2}$ NPK; full compost and $\frac{3}{4}$ NPK; compared with non-SRI methods with full NPK, no fertilizer (absolute control), and farmers' practice, the latter constituting the realistic control treatment. Other practices included with each SRI and modified SRI treatment were transplanting young rice seedlings (14 DOS) singly per hill, with spacing of 25 × 25 cm, and alternate wetting and drying (AWD).

Table 5. Costs and returns estimates of rice production with application of different types of fertilizers under SRI and non-SRI plots, average for two seasons, 2018 and 2019 (000 Naira ha^{-1}).

	SRI			Non-SRI			Change (%)			*t*-Test
Variable	**Full Compost (SRI 1)**	**$\frac{1}{2}$ NPK and $\frac{1}{2}$ Compost (SRI 2)**	**Full Compost and $\frac{3}{4}$ NPK (SRI 3)**	**Full NPK (MSRI 1)**	**Absolute Control: NoFertilizer (MSRI 2)**	**FP**	**SRI vs. Full NPK**	**SRI vs. Absolute Control**	**SRI vs. FP**	**SRI vs. FP**
Cost of land cultivated	35.3	35.3	35.3	35.3	35.3	35.3	0	0	0	NA
Cost of seed used	0.8	0.8	0.8	0.8	0.8	22.8	0	0	(−97)	47.8 ***
Cost of fertilizer applied	17.5	27.7	43.2	50.5	0	74.6	(−65)–(−14)	na	(−77)–(−42)	0.9
Cost of labor employed	119.8	119.9	119.7	120.6	92.9	99.2	−1	29	21	120 ***
Cost of chemicals applied	5.8	5.8	5.8	5.8	5.8	3.8	0	0	53	−16.2 ***
Cost of water used	6.2	6.2	6.2	6.2	6.2	6.2	0	0	0	NA
Cost of transport	17.4	17.5	17.4	18.5	5.0	9.0	(−6)–(−5)	250–253	94–95	−82.7 ***
Cost of empty bags used	11.3	11.5	11.4	12.2	3.5	6.7	(−8)–(−6)	225–233	69–73	−62.6 ***
Total cost of production	214.0	224.7	239.7	249.8	160.2	257.5	(−14)–(−4)	34–50	(−17)–(−7)	−7.2 ***
Yield (1000 kg/ha)	8.2	8.1	8.3	8.7	4.1	5.9	(−8)–(−5)	95–100	36–39	−55.5 ***
Revenue	860.5	842.3	862.2	913.4	426.6	616.7	(−8)–(−6)	97–102	37–40	−55.2 ***
Net return	646.5	617.6	622.4	663.6	266.4	359.1	(−7)–(−3)	132–143	132–143	−98.8 ***
Return on investment	3.03	2.76	2.61	2.67	1.83	1.43	(−2)–13	43–66	43–66	−60.9 ***

Change represents the gain or loss between SRI and non-SRI; MSRI = modified SRI *t*-test = difference test between SRI and FP (farmers' practices); At the time the survey was conducted, USD 1 was equivalent to NGN 445; NA = Not Available; *** < 0.01.

The two-year average total fertilizer cost for SRI was 4–14% lower than for the full compost treatment, and 7–17% lower than for farmers' practice; but it was 34–50% higher than for the absolute control (no fertilization). The two-year total cost of SRI practice averaged USD 508 ha^{-1}, with full compost and $\frac{3}{4}$ NPK being the costliest treatment (Table 5). For non-SRI trials, the total cost across the two-year period averaged USD 500 ha^{-1}, hardly different. However, there was a significant average total cost saving of 12% with SRI vs. farmers' practices, which were overall the more expensive method of rice farming.

4. Discussion

Knowing and using the most productive and profitable set of SRI practices for rice farms in northern Nigeria is important for moving toward the government's goal of national self-sufficiency for rice.

In this study, different sets of SRI treatments were evaluated, as well as farmers' conventional methods of farming rice. The 11 DOS, 25 × 25 cm spacing, SRI/AWD, and full compost treatments practically provided the highest yields with greatest returns on investment. These respective practices are highlighted as being the main contributors to the performance of SRI, and their combination can be regarded as the best-bet SRI practices most suitable to the study area. As explained in the introduction, we were not able to evaluate the impact of mechanical, soil-aerating weeding which has been seen to be one of the most impactful SRI practices [18], so this should probably also be included in best-bet SRI recommendations, but we cannot provide evidence from our trials for this.

The SRI treatments that included the best-bet SRI practices had rice yields that ranged from 8.2–11.4 t ha^{-1}, which is five or more times higher than the current national average yield of about 1.6 t ha^{-1}, and three or more times higher than the average yield in West Africa, currently about 2.4 t ha^{-1} [6]. This suggests that with the land area under rice cultivation in Nigeria, at present about 5.3 million ha, national rice production using the best-bet SRI methods could be several times greater than national demand, other things being equal.

The best-bet SRI practices that are identified here are well-adapted to the rice-growing conditions in northern Nigeria. For other parts of the country, similar evaluations should be made to see what modifications should be considered, if any, for different agroecological circumstances. With optimizing adjustments, it should be possible to get similar results as seen in Zamfara State. In general, the results of our study are consistent with the original set of SRI practices in terms of seedling age at transplanting, spacing pattern, and irrigation regimes that were assembled and validated by Fr. Henri de Laulanié in Madagascar for enhanced yield [16,19,20].

There was no significant difference seen in the cost of production between the best-bet SRI practices and farmers' traditional methods. It is sometimes asserted that the costs of production are higher under SRI, mostly due to increased labor requirements. This can apply at an initial stage of production when farmers are not yet experienced with SRI principles and practices [21]. However, over time (starting from the second year), through a process of learning by doing, the cost of labor under SRI tends to fall.

This was the case in this study, as the cost of labor as well as the total costs of production were less in the 2019 season compared to 2018. It can be inferred that with more years of experience with SRI practice, the cost of rice production based on SRI practices would become lower than alternative practices in Nigeria, which would make it more accessible to resource-poor farmers in the country.

Rice production with farmers' present irrigation techniques was profitable, but it was substantially lower than all of the SRI treatments assessed in this study. In Nigeria, evidence of positive returns from irrigated rice production has been reported in previous studies [22–26]. However, the net returns from these studies are usually less than USD 225 ha^{-1} [24,26], and the ROI was less than 1 per Naira invested per hectare. We found that the ROI for best-bet SRI ranged from 3.0–3.7 for every naira invested ha^{-1}. This indicates that best-bet SRI has the potential not only to triple farmers' yield, but also to raise the profitability of their rice production, without requiring their increased expenditure.

ROI was highest with reliance on compost rather than NPK, although the full-compost application was second to full-NPK in terms of yield performance. However, there is an issue of the availability of compost which needs to be considered. Although, knowledge and use of SRI are growing quickly among farmers in most developing countries, and particularly in Asia, statistics on this system of rice farming are still very limited for Africa, and especially in Nigeria regarding the profitability of SRI.

The findings of one study done in Nigeria run counter to our results, both in terms of yield and net returns [27]. However, those findings were specific to Adamawa State in eastern Nigeria, and we note that the SRI crop in these trials was established with direct seeding, planting 5–8 seeds per hole, which is counter to SRI recommendations and theory. There was in these trials thus no reduction in plant density, an essential feature of SRI methodology. Furthermore, the fertilization practices used were not reported, and it is not clear how well the soil and water were managed. So, that study does not provide a very satisfactory benchmark for assessing SRI practices in Nigeria as a whole. Similar studies to ours should be undertaken in other zones, but the scope and duration of this study should make SRI of interest for farmers, researchers, and policymakers alike.

5. Conclusions

Rice production under both SRI and non-SRI practices was profitable in our evaluation, although there were some important differences. The 11 DOS treatment was found to be very productive in terms of yield (10.2 t ha^{-1}) and more profitable (ROI = 3.25). Transplanting seedlings with spacing of 25 $\times$ 25 cm was found similarly to be the most productive practice (11.4 t ha^{-1}) and most profitable (ROI = 3.7). The irrigation regime of AWD was considerably better than farmers' current method of continuously flooding rice fields, AWD raising yield by 4.6 t ha^{-1} (by 128%) and giving a ROI of 2.5 (280% more than farmer practice).

Our research suggests that the best-bet SRI combination, the one most suitable for improving productivity and also sustainably raising income levels in the study area, would be 11 DOS with 25 $\times$ 25 cm spacing, AWD, and application of 5 tons of compost ha^{-1}. SRI management of irrigated rice cropping shows great potential for Nigeria, a production strategy more advantageous than the current methods used by resource-poor farmers.

Making recommendations on the use of fertilizer is complicated by the fact that both farmers and the government must reckon that the costs of inorganic fertilizer, already high, are more likely to rise in the future than to decline. Further fertilizer price rises will make rice production with present methods more expensive for farmers, or for the government if it tries to compensate for the higher prices through subsidization. This prospect makes present investment in developing organic means of improving or sustaining soil fertility in Nigeria, particularly in the north, very justifiable economically.

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