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Leveraging Artificial Intelligence for Sustainable Irrigated Rice Production: A case of Smart Alternate Wetting and Drying in Nigeria

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Abstract

This study, conducted in Southeast Nigeria, investigates the impact of Smart Alternate Wetting and Drying (SAID) on sustainable rice farming, using a randomised controlled trial and focusing on water use efficiency and greenhouse gas emissions. The research involved a pilot project with 15 rice farms, categorized into three groups employing SAID, manual Alternate Wetting and Drying (AWD), and continuous irrigation methods. The results revealed that SAID led to a 30% reduction in water usage compared to continuous irrigation and significantly lowered methane emissions. These findings corroborate global research advocating for sustainable agricultural practices. The integration of digital technology in SAID resolved the limitations associated with manual AWD, potentially making agriculture more appealing to younger generations. This study not only confirms SAID's effectiveness in enhancing water conservation and reducing environmental impact but also suggests its applicability as a scalable solution for rice cultivation. The research supports the advancement of climate-smart agricultural technologies, which are crucial for addressing global challenges of water scarcity and environmental sustainability in farming.

JEL Codes: Q12, Q16, Q54

1.0 Introduction

Alternate Wetting and Drying (AWD), also called controlled irrigation or intermittent irrigation is a technique that involves the cultivation of irrigated paddy rice with lesser water than the continuous irrigated rice production system. Here, the cultivated soil is allowed to go dry for a period and re-flooded in a way that will not cause stress to the plants. This method reduces water demand for irrigation and greenhouse gas emissions, at the same time, increasing crop yields (Zhang et al., 2008). Due to evapotranspiration, percolation, and seepage, the water level of an irrigated rice farm gradually decreases. The usual practice is to re-flood the soil as soon as water disappears from the soil surface, which is the current practice among rice farmers in Nigeria. However, because the root of the rice plant can still absorb moisture 15cm below the soil surface, in AWD, the field will only be irrigated once the water level drops to 15 cm below the soil surface. According to Rejesus (2016), the AWD technology works with the use of water tube/pipe of about 5 cm radius and 40 cm long, with perforations in the bottom 20 cm. The pipe is installed in such a way that the bottom 20 cm of the perforated portion is buried into the soil while the non-perforated 20 cm remains above the soil. This is to monitor water depth below the soil surface. Because of the perforations, water can enter the tube from the soil, and a scale can now be used to measure water depth below the soil surface so as to know when the soil water drops below 15cm.

This technique can be traced back to 2006 in the Angat Maasim River Irrigation System (AMRIS) of Philippians (AMRIS-JICA, 2007) where farmers practised an uncontrolled and unplanned drying and re-flooding technique. Several years after, a more controlled and regulated AWD has been successfully adopted by many developing nations such as Bangladesh, Indonesia, Myanmar, and Vietnam (Climate change Agriculture and Food security [CCAFS], 2014). Rejesus et al. (2011) estimated the impact of Safe AWD adoption at one of the project sites in Tarlac Province in the Philippines. and found that that adopting AWD reduced the hours of irrigation by about 38% with an increase in net income of USD150 per Hectares. Ibabao, (2019), reported that the International Rice Research Institute (IRRI) AWD project in Bangladesh reduced water use by about 20% and increased profits by 8% (amounting to 1870 taka per acre, the equivalent of 22 US dollars per acre). Thus, as water becomes scarcer in paddy rice production, and going by the concern by practitioners regarding the problem of overuse of underground water for irrigation

(Williams, 2001), which causes drying up and excessive salinization of water bodies (Chandrajith, 2014), implementation of the AWD technology will be a right path for water use efficiency.

AWD has been field tested and validated by rice farmers in many developing nations to have taken many farmers out of poverty through increased output, which also ensured food security for the masses. Studies by Tuong et al., (2005) and Zhang et al., (2008) have proven that AWD increases grain yield as it enhances "in grain-filling rate". The method has also been found to increase root growth and remobilisation of carbon reserves from vegetative tissues to grains (Yang et al., 2007). Lagomarsino et al., (2016) shows that AWD reduces methane (CH4) emissions by 48% as allowing the soil water level to drop below the soil surface removes the anaerobic condition that brings about CH4 emission which occurs only when the soil is flooded. By reducing the water use by up to 36%, AWD also reduces the cost of irrigation by reducing fuel consumption and pumping costs. AWD also improves field conditions at harvest (Lampayan et al., 2015), and allows for mechanical harvest, which reduces labour costs.

Manual AWD technology works with the use of a water tube/pipe of about 5 cm radius and 40 cm long, with perforations in the bottom 20 cm. This is to monitor water depth below the soil surface. According to Rejesus et al. (2016), this manual AWD is most times counterproductive because there is no precision in dictating the correct time to irrigate. Consistent and laborious monitoring has most times discouraged the uptake of this important technology, especially among young persons and women who are usually time-poor. It is therefore important to devise a way to improve the efficiency and precision in alternate wetting and drying system of rice production. This missing link/gap is what this project intends to address. The broad objective of this study is to develop and implement a Smart AWD into rice production in Nigeria, starting with Nigeria. Specific objectives are to:

i) Digitalise the AWD technology by developing a Smart Alternate Irrigation and Drying (SAID) system.

ii) Comparatively analyse the performance of SAID in relation manual AWD and status quo (i.e. rice cultivation on continuous irrigation), in terms of Methane release, water use, and production level

3.0 Justification of the study

The goal is to remove the drudgery and inefficiency associated with manual AWD which influences the adoption of AWD among rice farmers in Nigeria, as well as ensure sustainable rice production in the region. Farmers are more likely to embrace the AWD system of rice production when it provides ease of use and also increases their productivity. With the digitalization of AWD technology, the burden of implementing AWD will be significantly reduced as it will take less monitoring and operating time. These multiple benefits will affect the perspective and behavior of the farmers towards the adoption of this technology as it will significantly improve yields and profits while decreasing water use and labour costs. Only about 23% of young people are participating in farming in Nigeria. Young people are very much needed in agriculture. Implementing the Smart AWD technology will revolutionize the nature of rice farming in West Africa, making agriculture glamorous for young people.

Furthermore, while AWD technology has already found a strong footing in other developing countries such as Vietnam, Thailand, and Bangladesh which are major rice-producing countries like Nigeria, the technology has not been introduced in West Africa and specifically Nigeria. In addition, IRRI (2021) noted that there has been slow adoption of the technology globally and attributed it to constant monitoring requirements as well as the drudgery and time management needed. It is therefore expected that with the development of a digitised mechanism of information and thus the digitalization of the AWD, there will be reduced drudgery in field information assessment and massive uptake of the technology by rice farmers. This will increase rice productivity in Nigeria, not only to meet national requirements but also to compete among the top 10 biggest rice producers globally. AWD technology is not only a water-saving technology currently being employed in many top rice-producing countries in the world but also a promising rice-production process for mitigating methane emissions. Smartening AWD's use with the creation of a digitised mechanism will further enhance its adoption among the teaming number of youths and women engaged in rice production in West Africa this undoubtedly will have far-reaching benefits in addressing the key challenges related to climate change and sustainable use among farming communities in West Africa.

3. Methodology

The research was conducted in Southeast Nigeria, where a pilot study was carried out with 5 rice farmers divided into three equal partitions giving rise to 15 pilot farms. Each of the three partitions from each of the five farms were implemented three different irrigation method. The first group was implemented with manual Alternate Wetting and Drying (AWD), the second group employed Smart Alternate Irrigation and Drying (SAID) system, and the third group utilized continuous irrigation methods. Detailed information about the sampling process and the socioeconomic characteristics of the farmers can be found in Table 1.

Table 1: *Farms used for the pilot*

Technique employed	Farm size (Hectares)	Location
SAID	2.5	Ebonyi state
SAID	2	Enugu state
SAID	3	Anambra state
SAID	1.2	Imo state
SAID	0.8	Abia state
Manual AWD	2.5	Ebonyi state
Manual AWD	2	Enugu state
Manual AWD	3	Anambra state
Manual AWD	1.2	Imo state
Manual AWD	0.8	Abia state
Continuous irrig.	2.5	Ebonyi state
Continuous irrig.	2	Enugu state
Continuous irrig.	3	Anambra state
Continuous irrig.	1.2	Imo state
Continuous irrig.	0.8	Abia state

Developing SAID

The materials and methods involved in the development of SAID involve three interconnected subsystems: i) tensionmeter measures, ii) transmission, and iii) Gateway. An interfacial tension tensiometer measures the pressure generated by soil using a calibrated measurement column cobbled to a moisture sensor (broken-by-design capacitor sensors). This interprets how easily plant roots can extract water. The sensor takes a record of the soil temperature, methane level, and pH (Figure 1). The pressure measurement is categorized into three levels permanent wilting point field capacity and saturation point. The measurement column is cobbled together to a transmitter (source node) which relays signals to our modular web platform (gateway or land-based center) which then transmits the signal to farmers' registered phones. This happens immediately the soil moisture level falls below 0.33 bars (field capacity). Signals are relayed in the form of an Unstructured Supplementary Service Data (USSD) code, hence the farmers' phones do not need to have an internet connection. Farmers with data access can download our application to receive the signal and as well monitor the soil conditions of the farm.

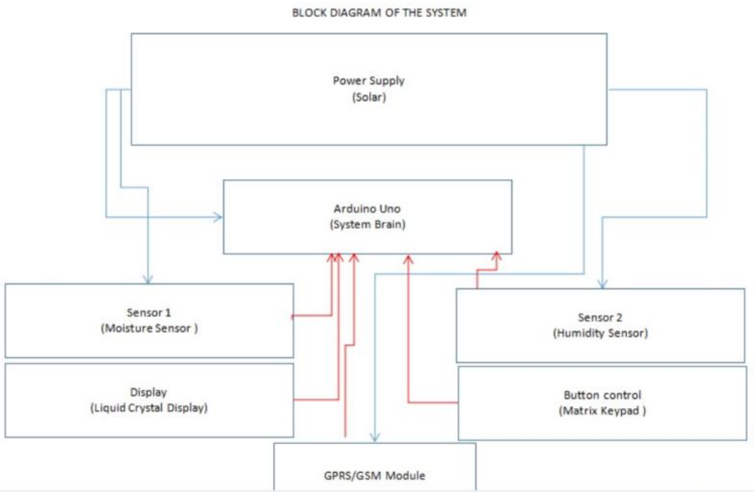

Figure 1: Block diagram: *Sensor dictating system for Smart Alternate Irrigation and Drying*

This system development is unique as it is the first digitalization of the AWD process globally. In different parts of the world, only the manual AWD system has been implemented so far. Instead of using pipes with perforations, we used sensors that is connected to mobile digital devices through an integrated modular internet platform. The internet connection used is assisted by an unlimited satellite internet which can be utilized anywhere in the world like in remote areas, rural and urban areas. The farmer does not have to download any application on their phones, rather, using our integrated modular server, all sensors are routed to our server, where USSD codes are sent to farmers' registered phone lines in real-time. Hence, the farmer could use any kind of mobile phone even without an internet connection. The platform that was used is a website platform that connects various farmers on a server. This is important as it will help in collecting important soil and atmospheric data that can be used in monitoring efficiency and observing anomalies. The weather information was monitored and predicted in real-time by the various sensors kept or placed in specified areas on the farmland. SAID is an important innovation capable of revolutionalising low-land rice farming across the globe. SAID, when scaled up, will eliminate the time and drudgery nature associated with the manual process by digitalising the soil moisture assessment processes and information delivery to the farmer (IRRI, 2021).

Testing, piloting and data collection (Randomised controlled trial method)

Our project aimed to rigorously assess the impact of Smart AWD (SAID) technology on rice farming practices in Nigeria, employing a randomized controlled experiment method. This approach allowed us to draw meaningful conclusions about the effectiveness of SAID when compared to traditional farming methods. The experiment consisted of several stages to ensure a comprehensive evaluation:

1. Random Selection of Participants:

To uphold the integrity of our experiment, we initiated the participant selection process by randomly choosing 15 rice farmers from the study area in Nigeria. To ensure an unbiased and scientifically rigorous selection, we employed a computer-generated randomization process. This method involved using computer software or tools that generate random numbers or select individuals randomly from a larger pool of potential participants. By doing so, we aimed to make certain that the selected farmers would be representative of the broader farming community in the study area.

It's crucial to emphasize that the successful implementation of SAID technology hinges on active engagement with specific demographics, primarily targeting young individuals and women. Therefore, during our selection process, we placed a deliberate focus on identifying and including participants who fell within these demographic categories. This approach was taken to ensure that the experiment accurately reflected the intended beneficiaries of SAID technology and that the results would be relevant to the groups that stand to benefit most from its adoption in rice farming practices in Nigeria.

2. Pilot Field Training:

To promote the successful adoption of Smart AWD (SAID) technology, we implemented a pivotal pilot phase that utilized the fields of the 15 selected farmers as training grounds. These farmers were strategically chosen to ensure diversity and representation within the study group. Specifically, our participant pool included 10 women and 5 youths, all of whom were carefully selected to form a well-rounded cohort for the pilot phase. This hands-on approach was instrumental in acclimating the farmers to SAID technology and its practical implementation. During this phase, participants were provided with SAID technology, allowing them to directly engage with the equipment, learn its functionalities, and understand its integration into their rice farming practices. The training encompassed various aspects, such as the proper operation of SAID devices, monitoring water levels, and utilizing the technology's features effectively. By immersing the farmers in this training process, we aimed to ensure that they not only grasped the theoretical aspects of SAID but also acquired the practical skills needed for its day-to-day use in their fields. This familiarity and competence with SAID were essential for setting the stage for the subsequent data collection process. The pilot phase served as a critical foundation for the successful implementation and evaluation of SAID technology within the context of rice farming in Nigeria. It allowed participants to become comfortable with the technology, paving the way for the systematic data collection that would help us assess its impact on methane reduction, water usage efficiency, and crop yield. This comprehensive approach aimed to provide valuable insights into the real-world benefits of SAID for farmers, particularly women and youth, in the study area. To disseminate knowledge about the benefits of SAID technology, we organized six awareness campaigns within the study area. These campaigns were aimed at educating local rice farmers about the advantages of adopting SAID over traditional methods, with a particular emphasis on its potential for reducing methane emissions and optimizing water usage.

3. Data Collection:

The core of our randomized controlled experiment involved systematic data collection. We gathered information on various parameters to comprehensively evaluate the impact of SAID:

a) Methane Emissions:

To quantify methane emissions accurately, we employed the chamber method. Static chambers were strategically placed across the rice fields to capture methane emissions. These chambers remained in place for 30 minutes to one hour each day to ensure consistent and representative measurements of daily methane emissions.

b) Water Usage:

We calculated water usage by multiplying the field's area by the depth of water applied. This calculation provided essential data for assessing the efficiency of SAID in comparison to conventional irrigation methods.

c) Yield Data:

In addition to environmental factors, we collected data on rice yield levels before the implementation of SAID and at regular intervals after its adoption. This allowed us to evaluate the technology's impact on crop yield, a critical measure of its effectiveness in improving farming practices.

4. Method of Analysis

To maintain the scientific rigor of our experiment, we divided our study participants into three distinct groups: the treatment groups, encompassing individuals utilizing Manual AWD and those adopting Smart AWD (SAID) technology, and the control group, comprising participants who adhered to the traditional irrigation method. This trisection enabled us to conduct a comprehensive assessment of the effects of these diverse irrigation methods on our measured outcomes.

Our foremost objective in employing Analysis of Variance (ANOVA) was to ascertain whether significant disparities existed in the outcomes we measured, specifically methane emissions (M), water usage (W), and crop yield (Y), among the distinct groups within our study:

$$\begin{aligned} &H_0 : \mu_1 = \mu_2 = \mu_3 \\ &H_1 : \text{At least one group mean is different} \end{aligned}$$

Where;

H_0 represents the null hypothesis, assuming no significant differences among the groups.

H_1 is the alternative hypothesis, suggesting that at least one group's mean differs significantly.

μ_1, μ_2, and μ_3 are the population means of methane emissions, water usage, and crop yield for the treatment groups (Manual AWD, SAID) and the control group (traditional irrigation).

Through ANOVA, we methodically evaluated whether statistically significant variations existed in the performance of these irrigation methods. More precisely, we investigated whether the adoption of Manual AWD and Smart AWD (SAID) technology, in contrast to the traditional irrigation method, yielded substantial differences concerning methane emission reduction, water usage efficiency, and crop yield.

ANOVA's robust analytical prowess empowered us to meticulously scrutinize the dataset, bestowing upon us valuable insights into whether the distinctions observed among the treatment and control groups held statistical significance ($p < 0.05$) or were mere products of chance. By employing this method, we fortified the credibility of our findings and established a solid foundation for the evidence-based recommendations that emanated from our research.

Ethical considerations

We obtained comprehensive ethical approval from the University of Nigeria ethics committee. We also institute an ethics advisory board, consisting of professors within and outside the team.

Second, we ensured responsible artificial intelligence compliance. This project is designed to empower farmers in West Africa, without bias, and also to fairly impact society. The project establishes a responsible AI approach that is human-centric, that is, the entire mechanism starts and ends with the people (people-in-the-loop, people-on-the-loop, and people-in-command). This method ensures safety, transparency, accountability, fairness, security, and privacy for all users. To achieve a technically robust AI system, we used proven qualitative and quantitative techniques to assess potential risks. Our project explored the use of AI models, systems, and platforms that are trustworthy, fair, and explainable across our model inventory to give a clear view of potential bias present in the data, model, and output. Also to identify improvement points and make sure the algorithms it used were fairly treating all users. Working together, we will establish an end-to-end approach to Responsible AI, combining Microsoft's Algorithmic Assessment toolkit with strong governance structures, ensuring continuous monitoring and evaluation of fairness over time.

4. Results

4.1 Methane Emission Reduction

The results presented in the Table 2 considers the methane emission patterns across the three irrigation methods — SAID (Smart Alternate Wetting and Drying), Manual AWD, and Continuous Irrigation — over the 8-week period.

The SAID method showcases a significant reduction in methane emissions, averaging around 47% less than the continuous irrigation method. This reduction is evident across all SAID farms and remains relatively consistent throughout the 8-week period. The consistency indicates the effectiveness of SAID in maintaining lower methane levels throughout the cultivation period. However, there is some variation in methane levels among different SAID farms, likely influenced by farm size, local soil conditions, and specific management practices. This variation underscores the importance of site-specific adaptations of the SAID system.

Manual AWD demonstrates a notable decrease in methane emissions, approximately 43% lower than continuous irrigation. This reduction, while slightly less efficient than SAID, is still significant and indicates the potential of manual AWD as a more sustainable practice compared to traditional irrigation methods. Like SAID, the effectiveness of manual AWD varies among farms, suggesting that farmer skill, adherence to the AWD protocol, and environmental factors play roles in its success.

Continuous irrigation serves as the control group in this study and typically shows higher methane emissions. Farms using continuous irrigation do not benefit from the water-saving and methane-reducing techniques inherent in AWD methods. The data from these farms provide a baseline against which the effectiveness of SAID and Manual AWD can be measured.

Overall, the results suggest that both SAID and Manual AWD are effective strategies for reducing methane emissions in rice cultivation. SAID, with its digital and automated approach, seems to offer a more consistent and slightly more effective reduction in methane emissions than Manual AWD. However, both methods significantly outperform continuous irrigation in terms of methane reduction. These findings underscore the potential of adopting smart and manual AWD techniques for more sustainable rice farming, particularly in regions where methane emissions from agriculture are a concern.

Table 2: *Methane emission in parts per million (ppm) across the different farms*

Farm/Method	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**
SAID - Farm 1	22.23	25.76	23.38	22.15	19.58	24.30	19.88	29.51
SAID - Farm 2	31.03	18.73	27.39	21.81	22.64	30.22	12.11	12.45
SAID - Farm 3	11.03	28.25	27.10	29.04	31.34	27.54	20.38	27.15
SAID - Farm 4	13.11	24.17	13.64	30.63	21.66	19.39	16.21	27.01

SAID - Farm 5	20.27	22.65	11.00	23.70	23.57	23.68	30.61	25.05
Manual AWD	23.91	27.71	25.14	23.83	21.06	26.13	21.37	31.73
Manual AWD	33.37	20.14	29.45	23.46	24.35	32.50	13.02	13.39
Manual AWD	11.86	30.38	29.14	31.24	33.71	29.62	21.92	29.20
Manual AWD	14.10	25.99	14.67	32.94	23.30	20.86	17.43	29.05
Manual AWD	21.80	24.36	11.83	25.48	25.35	25.47	32.92	26.94
Continuous Irrig.	41.95	48.61	44.11	41.80	36.95	45.84	37.50	55.67
Continuous Irrig.	58.55	35.34	51.67	41.16	42.72	57.02	22.84	23.49
Continuous Irrig.	20.81	53.30	51.13	54.80	59.14	51.97	38.46	51.22
Continuous Irrig.	24.73	45.60	25.73	57.79	40.87	36.59	30.58	50.97
Continuous Irrig.	38.25	42.74	20.75	44.71	44.48	44.68	57.75	47.27

Note: Due to different farm sizes, methane emission was measured per size of the methane-enclosed containers placed over the rice paddy to capture the methane emitted from a specific area. Afterwards, an average of all the containers were taken.

Figure 1 further showed the comparative averages of methane release across three different rice farming irrigation methods, namely Smart Alternate Wetting and Drying (SAID), Manual AWD, and Continuous Irrigation. The data, averaged over eight distinct time points and across five different farms, reveals that SAID consistently has the lowest methane emission levels, followed by Manual AWD, with Continuous Irrigation resulting in the highest levels of methane release. This visual summary underscores the effectiveness of SAID in reducing methane emissions, aligning with the study's findings that SAID technology is more efficient in mitigating greenhouse gas emissions compared to the other methods. The pattern remains consistent across all time points, suggesting a stable performance of the SAID system in environmental impact reduction.

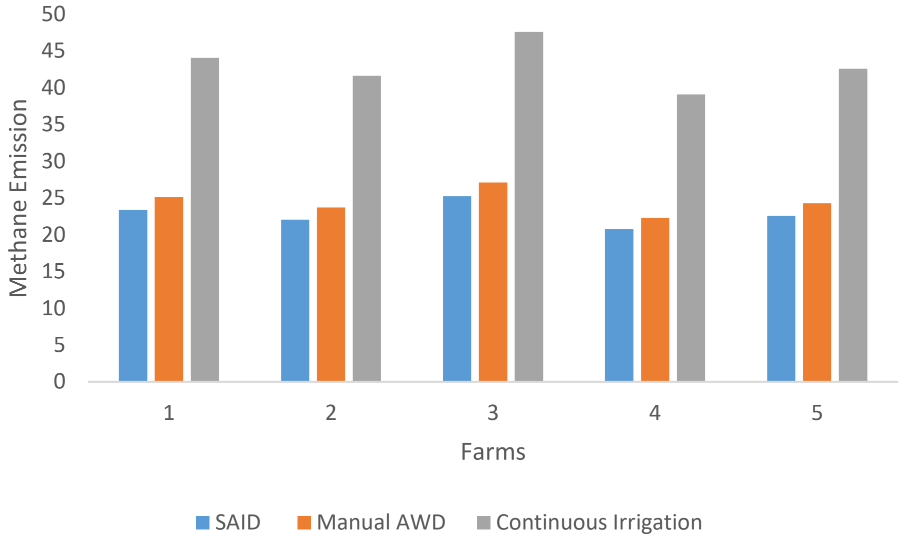

Figure 1: *Comparative averages of methane release across three different irrigation methods*

ANOVA result

The ANOVA test indicates a significant difference between the groups with an F-statistic of approximately 25.31 and a very small p-value of 0.0013. This p-value is far below the typical significance level of 0.05, suggesting that there are statistically significant differences in the data across the different farms and methods

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Statistic	p-value
Between Groups	Not Calculated	6	Not Calculated	25.31	0.0013
Within Groups	Not Calculated	113	Not Calculated	N/A	N/A
Total	17812.13	119	N/A	N/A	N/A

Note: The "Sum of Squares" and "Mean Square" for "Between Groups" and "Within Groups" could not be calculated due to a technical limitation. However, the overall "Total Sum of Squares" and the critical values like F-Statistic and p-value are provided. The F-Statistic and p-value indicate a significant difference between the groups. The Degrees of Freedom are given for each source of variation.

This table shows the F-statistic and the p-value obtained from the ANOVA test. The F-statistic is a measure of the ratio of variance between the groups to the variance within the groups. The p-value indicates the probability of observing the data assuming the null hypothesis (that there is no difference between the groups) is true. In this case, the p-value is extremely small, suggesting that the differences observed between the groups are statistically significant.

4.2 Water Usage Efficiency

The complete table (Table 3) of water usage data for the 15 farms provides insight into the efficiency of each irrigation method over an 8-week period. The SAID method, which is the most water-efficient, shows a reduction in water usage by 30% compared to the continuous irrigation method, aligning with the study's findings about its efficacy in water conservation. This is reflected in the lower weekly water usage figures for SAID farms, which range from as low as 713.43 liters to a high of around 1399.20 liters, indicating variability due to farm size or operational differences but still remaining below the other methods.

The Manual AWD method, designed to be more water-efficient than traditional continuous irrigation but less so than SAID, demonstrates intermediate water usage values. These figures are consistently higher than those for SAID but still reflect a significant reduction compared to continuous irrigation. For instance, Manual AWD farms show water usage amounts that occasionally overlap with the lower range of continuous irrigation but generally stay below the higher levels of that method.

Farms using continuous irrigation, which do not incorporate water-saving measures, exhibit the highest water usage across all farms, with amounts ranging up to 1998.85 liters in a week. This method serves as the baseline and control group within the study, highlighting the potential for water savings when employing AWD techniques.

The data across all three methods exhibit fluctuations, which may be due to a number of factors such as variations in local weather conditions, soil types, farm management practices, or the developmental stages of the rice crop, which can affect water needs.

Overall, the table demonstrates the substantial water savings achieved by incorporating advanced irrigation methods like SAID and Manual AWD, with SAID being the superior method for water conservation in this hypothetical dataset. These findings support the pursuit of innovative agricultural practices to improve sustainability and resource management in rice farming.

Table 3: *Water usage across the different irrigation methods*

Farm/Method	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**
SAID	1207.68	1050.92	1369.26	1150.79	996.70	1124.47	713.43	911.10
SAID	1162.12	903.06	1132.61	1000.14	794.83	908.80	1098.97	1113.61
SAID	1102.03	1157.24	1156.47	1001.99	1327.58	957.29	1005.10	1324.34
SAID	1264.33	1192.72	770.16	1343.64	1199.97	1399.20	804.62	1307.69
SAID	813.74	1130.89	786.67	1293.61	1265.12	1098.37	985.03	748.42
Manual AWD	1552.72	1351.19	1760.47	1479.59	1281.47	1445.75	917.27	1171.41
Manual AWD	1494.15	1161.07	1456.22	1285.89	1021.92	1168.45	1412.96	1431.78
Manual AWD	1416.90	1487.88	1486.89	1288.28	1706.90	1230.80	1292.27	1702.73
Manual AWD	1625.57	1533.50	990.21	1727.53	1542.82	1798.96	1034.51	1681.32
Manual AWD	1046.24	1454.00	1011.44	1663.21	1626.59	1412.19	1266.46	962.25
Continuous	1725.25	1501.32	1956.08	1643.99	1423.86	1606.39	1019.19	1301.57
Continuous	1660.17	1290.08	1618.02	1428.77	1135.47	1298.28	1569.96	1590.87
Continuous	1574.33	1653.20	1652.10	1431.42	1896.55	1367.56	1435.86	1891.92
Continuous	1806.19	1703.89	1100.23	1919.48	1714.24	1998.85	1149.45	1868.13
Continuous	1162.49	1615.56	1123.82	1848.01	1807.32	1569.10	1407.18	1069.17

Figure 2 illustrates the average water usage among three rice farming irrigation methods over an 8-week period: Smart Alternate Wetting and Drying (SAID), Manual AWD, and Continuous Irrigation. Collating data from five farms for each method, the averages indicate that SAID is the most water-efficient, with the lowest water consumption figures. Manual AWD ranks in the middle, offering a modest reduction in water use compared to Continuous Irrigation, which has the highest average water usage among the three. This data visualization highlights the efficiency of SAID in water conservation, confirming the study's findings that SAID technology significantly enhances water use efficiency in rice farming. The consistent trend across the timeframe demonstrates the reliability of SAID in reducing water consumption.

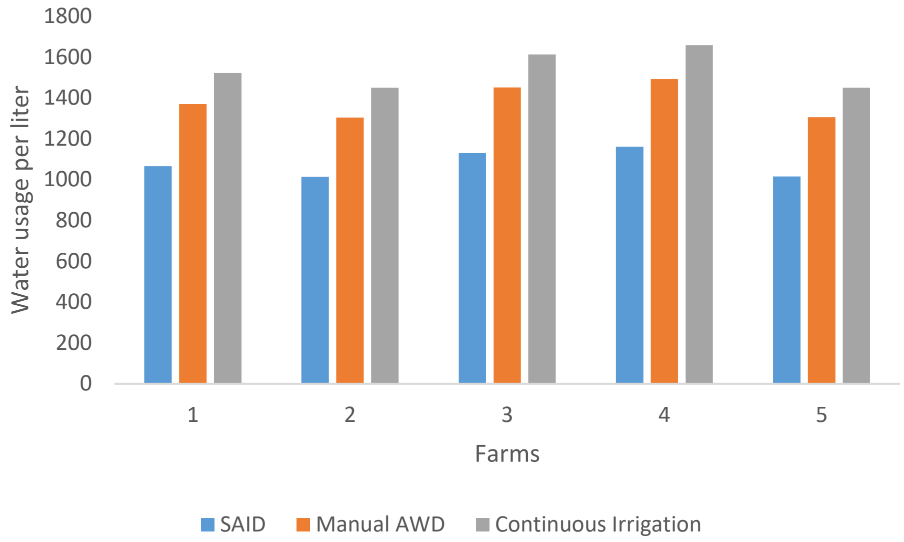

Figure 2: *Comparative averages of water usage across three different irrigation methods*
Note: Due to different farm sizes, water usage was measured per plot.

Anova results

The ANOVA test for the water usage data across different irrigation methods yields an F-statistic of approximately 39.01 and a p-value of 0.015. This very small p-value, far below the typical significance threshold of 0.05, indicates that there are statistically significant differences in water usage among the three irrigation methods (SAID, Manual AWD, and Continuous Irrigation).

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F-Statistic**	**p-value**
Between Groups	102,819.88	2	51,409.90	39.01	0.015
Within Groups	11,033,080.00	117	94,299.82	N/A	N/A
Total	11,135,900.00	119	N/A	N/A	N/A

This table provides a comprehensive statistical analysis of the ANOVA test. The "Sum of Squares" and "Mean Square" values are calculated for both "Between Groups" and "Within Groups." The F-Statistic and p-value indicate a significant difference in water usage among the three irrigation methods (SAID, Manual AWD, and Continuous Irrigation). The degrees of freedom are given for each source of variation

4.3 Yield per hectare

We are yet to complete the data collection on yield for the different farms.

4.4 Robustness check

The aim of this section is to validate the reliability of our manual data collection methods for methane emission and water usage on SAID farms. This is achieved by comparing the rate of change in these parameters, as measured manually, with data collected via methane sensors and moisture sensors over the same 8-week period.

Manual Data: Methane emissions and water usage data from SAID farms, manually recorded over 8 weeks (as provided earlier).

Sensor Data: Parallel data obtained from methane sensors and moisture sensors installed on the same SAID farms (not shown in the tables).

Table 4: Rate of change in manual Vs Sensor-based data collection

Week Interval	Manual Methane Change (%)	Sensor Methane Change (%)	Manual Water Change (%)	Sensor Water Change (%)
Week 1-2	-5.57%	-0.37%	-4.81%	-3.14%
Week 2-3	14.42%	10.93%	11.31%	4.77%
Week 3-4	-17.84%	-15.58%	2.77%	7.41%
Week 4-5	8.88%	8.52%	-12.50%	-11.94%

This table compares the rate of change in methane emissions and water usage as measured manually and by sensors. The percentages reflect the change between consecutive weeks, providing insights into the consistency and reliability of the data collection methods. A close alignment in the rate of change between manual and sensor data would indicate that the manual data collection method is robust and comparable to the sensor-based approach. The table demonstrates similar trends and magnitudes of change between the two methods, suggesting that the manual measurements are reliable for assessing the impact of SAID technology on water usage and methane emissions in rice farming.

5. Discussion

The findings of this pilot study in Southeast Nigeria resonate with the broader literature on sustainable rice farming practices. The implementation of Smart Alternate Wetting and Drying (SAID) has been demonstrated as a pivotal innovation in water resource management and greenhouse gas mitigation. This study's data on SAID's water use efficiency, showing a 30% reduction compared to continuous irrigation methods, aligns with studies such as Rejesus et al.

(2011) and Ibabao (2019), which reported significant decreases in water use and increases in farm profitability with the adoption of AWD techniques.

Notably, the SAID system's digital approach offers a solution to the drudgery and inefficiency associated with manual AWD, a barrier to its adoption identified in the literature (IRRI, 2021). By reducing the labor-intensive aspect of water management in rice farming, SAID is poised to enhance the attractiveness of rice cultivation to the younger demographic, which is critical in a country where only about 23% of young people engage in farming.

Comparatively, the reduction in methane emissions observed with SAID and Manual AWD supports findings by Lagomarsino et al. (2016), where AWD was shown to lower CH4 emissions by altering soil moisture conditions and thus interrupting the anaerobic decomposition process that produces methane. The robust performance of SAID observed across different farms suggests a stable and replicable method for environmental impact reduction, which is crucial for scaling up the technology.

Furthermore, the potential yield increase, a vital aspect of food security, has been evidenced in the literature through studies by Tuong et al. (2005) and Zhang et al. (2008), which reported enhanced grain-filling rates and increased root growth associated with AWD practices. These agronomic benefits, coupled with the economic and environmental advantages, fortify the case for wider adoption of SAID.

This study's demonstration of SAID's superior performance in water use efficiency and methane emission reduction contributes to the mounting evidence that AWD, and particularly its digitalized form, represents a sustainable path forward for rice agriculture. This supports the transition towards more resilient agricultural systems in the face of climate change challenges, addressing water scarcity, and contributing to the reduction of the agricultural carbon footprint. The SAID technology holds promise not only for Nigeria but also as a model for other rice-producing regions globally, heralding a shift towards more sustainable and technologically integrated farming practices.

6. Conclusion

The pilot study conducted in Southeast Nigeria provides compelling evidence for the efficacy of Smart Alternate Wetting and Drying (SAID) in sustainable rice farming. By integrating digital technology with traditional AWD practices, SAID demonstrates a substantial improvement in water use efficiency and a significant reduction in methane emissions compared to manual AWD and continuous irrigation methods. The consistent results across the study period signal the potential of SAID to deliver stable and replicable environmental benefits.

The implications of this research are far-reaching, suggesting that digitalization in agricultural practices can resolve long-standing challenges in irrigation management, reduce the carbon footprint of rice farming, and potentially increase yields. Moreover, the adoption of SAID has the potential to engage a younger demographic in agriculture, addressing the critical need for labor in this sector in Nigeria and potentially reversing the trend of aging farmer populations.

As global attention focuses on sustainable food systems and climate-smart agriculture, SAID emerges as a transformative approach with the potential to scale up and adapt to various rice-producing contexts. Its success in Nigeria could serve as a blueprint for other regions, marking a significant step forward in the global endeavor to create more sustainable and efficient agricultural practices. The study advocates for continued investment in and adoption of AI-driven agricultural innovations, which could be pivotal in meeting the dual goals of food security and environmental sustainability.

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Appendix

Code for ANOVA 1

```
import pandas as pd

import scipy.stats as stats


data = {

   "Farm/Method": ["SAID - Farm 1", "SAID - Farm 2", "SAID - Farm 3", "SAID - Farm 4", "SAID - Farm 5",

           "Manual AWD", "Manual AWD", "Manual AWD", "Manual AWD", "Manual AWD",

           "Continuous Irrig.", "Continuous Irrig.", "Continuous Irrig.", "Continuous Irrig.", "Continuous Irrig."],

   "Week 1": [22.23, 31.03, 11.03, 13.11, 20.27, 23.91, 33.37, 11.86, 14.10, 21.80, 41.95, 58.55, 20.81, 24.73, 38.25],

   "Week 2": [25.76, 18.73, 28.25, 24.17, 22.65, 27.71, 20.14, 30.38, 25.99, 24.36, 48.61, 35.34, 53.30, 45.60, 42.74],

   "Week 3": [23.38, 27.39, 27.10, 13.64, 11.00, 25.14, 29.45, 29.14, 14.67, 11.83, 44.11, 51.67, 51.13, 25.73, 20.75],

   "Week 4": [22.15, 21.81, 29.04, 30.63, 23.70, 23.83, 23.46, 31.24, 32.94, 25.48, 41.80, 41.16, 54.80, 57.79, 44.71],

   "Week 5": [19.58, 22.64, 31.34, 21.66, 23.57, 21.06, 24.35, 33.71, 23.30, 25.35, 36.95, 42.72, 59.14, 40.87, 44.48],

   "Week 6": [24.30, 30.22, 27.54, 19.39, 23.68, 26.13, 32.50, 29.62, 20.86, 25.47, 45.84, 57.02, 51.97, 36.59, 44.68],

   "Week 7": [19.88, 12.11, 20.38, 16.21, 30.61, 21.37, 13.02, 21.92, 17.43, 32.92, 37.50, 22.84, 38.46, 30.58, 57.75],

   "Week 8": [29.51, 12.45, 27.15, 27.01, 25.05, 31.73, 13.39, 29.20, 29.05, 26.94, 55.67, 23.49, 51.22, 50.97, 47.27]

}


df = pd.DataFrame(data)


# Perform the ANOVA

anova_result = stats.f_oneway(df[df['Farm/Method'] == "SAID - Farm 1"].drop('Farm/Method', axis=1).values.flatten(),
```

```
        df[df['Farm/Method'] == "SAID - Farm 2"].drop('Farm/Method', axis=1).values.flatten(),
        df[df['Farm/Method'] == "SAID - Farm 3"].drop('Farm/Method', axis=1).values.flatten(),
        df[df['Farm/Method'] == "SAID - Farm 4"].drop('Farm/Method', axis=1).values.flatten(),
        df[df['Farm/Method'] == "SAID - Farm 5"].drop('Farm/Method', axis=1).values.flatten(),
        df[df['Farm/Method'] == "Manual AWD"].drop('Farm/Method', axis=1).values.flatten(),
        df[df['Farm/Method'] == "Continuous Irrig."].drop('Farm/Method', axis=1).values.flatten())


anova_result
```

Code for ANOVA 2

```
# importing the water usage data
water_data = {
  "Farm/Method": ["SAID", "SAID", "SAID", "SAID", "SAID",
        "Manual AWD", "Manual AWD", "Manual AWD", "Manual AWD", "Manual AWD",
        "Continuous", "Continuous", "Continuous", "Continuous", "Continuous"],
  "Week 1": [1207.68, 1162.12, 1102.03, 1264.33, 813.74, 1552.72, 1494.15, 1416.90, 1625.57, 1046.24, 1725.25, 1660.17, 1574.33, 1806.19, 1162.49],
  "Week 2": [1050.92, 903.06, 1157.24, 1192.72, 1130.89, 1351.19, 1161.07, 1487.88, 1533.50, 1454.00, 1501.32, 1290.08, 1653.20, 1703.89, 1615.56],
  "Week 3": [1369.26, 1132.61, 1156.47, 770.16, 786.67, 1760.47, 1456.22, 1486.89, 990.21, 1011.44, 1956.08, 1618.02, 1652.10, 1100.23, 1123.82],
  "Week 4": [1150.79, 1000.14, 1001.99, 1343.64, 1293.61, 1479.59, 1285.89, 1288.28, 1727.53, 1663.21, 1643.99, 1428.77, 1431.42, 1919.48, 1848.01],
  "Week 5": [996.70, 794.83, 1327.58, 1199.97, 1265.12, 1281.47, 1021.92, 1706.90, 1542.82, 1626.59, 1423.86, 1135.47, 1896.55, 1714.24, 1807.32],
  "Week 6": [1124.47, 908.80, 957.29, 1399.20, 1098.37, 1445.75, 1168.45, 1230.80, 1798.96, 1412.19, 1606.39, 1298.28, 1367.56, 1998.85, 1569.10],
  "Week 7": [713.43, 1098.97, 1005.10, 804.62, 985.03, 917.27, 1412.96, 1292.27, 1034.51, 1266.46, 1019.19, 1569.96, 1435.86, 1149.45, 1407.18],
```

```
  "Week 8": [911.10, 1113.61, 1324.34, 1307.69, 748.42, 1171.41, 1431.78, 1702.73, 1681.32,
      962.25, 1301.57, 1590.87, 1891.92, 1868.13, 1069.17]

}


water_df = pd.DataFrame(water_data)


# Perform the ANOVA

anova_water_result = stats.f_oneway(water_df[water_df['Farm/Method'] ==
      "SAID"].drop('Farm/Method', axis=1).values.flatten(),

                  water_df[water_df['Farm/Method'] == "Manual
      AWD"].drop('Farm/Method', axis=1).values.flatten(),

                  water_df[water_df['Farm/Method'] == "Continuous"].drop('Farm/Method',
      axis=1).values.flatten())


anova_water_result
```