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DETERMINANT FACTORS OF CLIMATE-SMART RICE CULTIVATION PRODUCTION IN PASURUAN: TRANSLOG PRODUCTION FUNCTION APPROACH

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ABSTRACT

The agricultural sector is a contributor to greenhouse gas (GHG) emissions and a vulnerable victim of climate change at the same time. Climate change has affected food stability and security, including rice. It is an essential commodity to pay attention to in terms of quantity, quality, and continuity. Unsustainable rice cultivation practices can threaten it. Climate-smart rice cultivation (CSRC) can be a solution and needs to be introduced to respond to these challenges. CSRC is one of the programs carried out by The World Agroforestry Center (ICRAF) through The 'Rejoso Kita Phase 2' project in Pasuruan District to respond to existing farming practices that are unsustainable, such as excessive use of rice seeds, water for irrigation, fertilizer use, and pesticide use. This study aims to determine the production factors of CSRC using the transcendental logarithmic (Translog) production function approach. One hundred sixty-eight farmers in Pasuruan were involved in the farmer household survey collected through a structured digital questionnaire. The constructed production function model utilized nine variables. Seeds, N fertilizer, P fertilizer, K fertilizer, chemical pesticide, and chemical pesticide variables were statistically significant, with only variable of K fertilizer having a negative effect. Meanwhile, land size, organic fertilizer, and labor are not significant. The average productivity of farmers is higher than the average productivity of Pasuruan District. Combating global warming can be achieved without sacrificing yields, and it can provide a better understanding to encourage wider adoption of CSRC innovation technology. Intensive extension and mentoring related to CSRC components for farmers is an essential policy implication that needs to be implemented to maximize rice productivity and reduce negative externalities.

Keywords: *climate-smart rice cultivation, production function, transcendental logarithmic*

ABSTRAK

Sektor pertanian merupakan penyumbang emisi gas rumah kaca (GRK) sekaligus korban yang rentan terhadap perubahan iklim. Perubahan iklim telah memengaruhi stabilitas dan ketahanan pangan, termasuk beras, yang merupakan komoditas penting dari segi kuantitas, kualitas, dan keberlanjutan. Praktik budidaya padi yang tidak ramah lingkungan dapat menjadi ancaman. Budidaya Padi Ramah Lingkungan (BPRL) dapat menjadi solusi dan perlu diperkenalkan untuk menjawab tantangan ini. BPRL merupakan salah satu program yang dilakukan oleh World Agroforestry Center (ICRAF) melalui proyek 'Rejoso Kita Fase 2' di Kabupaten Pasuruan untuk merespons praktik pertanian yang kurang ramah lingkungan atau tidak berkelanjutan, seperti penggunaan benih padi, air irigasi, pupuk kimia, dan pestisida kimia yang berlebihan. Penelitian ini bertujuan untuk mengetahui faktor-faktor produksi dalam BPRL dengan pendekatan fungsi produksi Transcendental Logarithmic (Translog). Sebanyak 168 petani di Pasuruan terlibat dalam survei rumah tangga petani yang dikumpulkan melalui kuesioner digital terstruktur. Model fungsi produksi yang dibangun melibatkan sembilan variabel. Benih, pupuk unsur N, pupuk unsur P, pupuk unsur K, dan pestisida kimia menunjukkan pengaruh signifikan secara statistik, sedangkan pupuk K memberikan pengaruh negatif. Sementara itu, luas lahan, pupuk organik, dan tenaga kerja tidak terbukti signifikan secara statistik. Rata-rata produktivitas petani lebih tinggi dibandingkan rata-rata produktivitas Kabupaten Pasuruan. Mengatasi pemanasan global dapat dilakukan tanpa mengorbankan hasil panen, dan hal ini dapat memberikan pemahaman yang lebih baik untuk mendorong adopsi teknologi inovasi BPRL secara lebih luas. Penyuluhan dan pendampingan intensif terkait komponen BPRL bagi petani merupakan implikasi kebijakan penting yang perlu diterapkan untuk memaksimalkan produktivitas padi dan mengurangi dampak negatif eksternal.

Kata kunci: budidaya padi ramah lingkungan (bprl), fungsi produksi, transendental logarithmic (translog)

INTRODUCTION

The agricultural sector has played an important role not only as a food source but also as a contributor to greenhouse gas (GHG) emissions in recent decades. The agriculture sector contributes through almost half of methane (CH_4) emissions, two-thirds of nitrous oxide (N_2O) emissions, and three percent of carbon dioxide (CO_2) emissions from human activities in the world. These three compounds account for around 80% of contributors to global warming (29, 5, and 46 percent), so agriculture contributes around 15% to global warming (IPCC, 2023). It is projected that rice will be the second highest emission contributor (23%) below ruminant meat (33%) in 2030 (Ivanovich et al., 2023).

The agricultural sector is a contributor to GHG emissions and also a sector that is targeted (victimized) and vulnerable to climate change. Climate change has affected food stability and security (Prinz, 2009; Ray et al., 2023). The Food and Agriculture Organization (FAO) responded to the impacts and contributions of agriculture to climate change while contributing to sustainable development goals by issuing the concept of Climate Smart Agriculture (CSA) in 2010. The three pillars of CSA include (1) increasing sustainable agricultural productivity and income, (2) adapting and building resilience to climate change, and (3) mitigating and/or eliminating GHG emissions (FAO, 2013, 2019). The concept of climate-smart agriculture is not a universal approach or "one size fits all" but an approach appropriate to the specific social and environmental context that requires evaluating benefits and trade-offs.

Integration of a sustainable environment, agricultural innovation strategies, and development regulatory mechanisms are needed to reduce hostile environmental externalities (Aldy et al., 1998). Agricultural technology innovation can support rural structural transformation to provide broad benefits to farmers (IFAD, 2016). Agricultural technology innovation plays an important role in the development of human civilization from time to time, especially for the lives of farmers, by increasing production efficiency and maximizing farming profits. Rice, as the primary food crop in Indonesia, has transformed cultivation technology to support national food security within the sustainable development framework (Matsuura & Sakagami, 2022; Sutardi et al., 2023).

Since 2020, East Java Province has become the largest rice production center with the most extensive rice fields. However, this did not guarantee Indonesia's highest rice productivity because East Java Province still ranks third after Bali and West Java Provinces. Pasuruan District is one of the districts in East Java where most rice farmers still use conventional or unsustainable cultivation methods. Using excessive inputs is the main focus in the cultivation aspect, such as seeds used with conventional planting patterns with excessive seeds, continuous flooding irrigation, excessive chemical fertilizers, and reliance on chemical pesticides.

The conventional rice cultivation method triggers various problems that affect the quality of the rice produced. The average price of GKP (unhusked rice after harvest) in Pasuruan District was ranked second lowest out of 18 regencies observed in 2021. Even in 2022 and 2023, the quality of rice worsened, as indicated by the price of grain being ranked lowest (BPS 2022, 2023a, 2024a). Although farmers experienced various problems, the average rice productivity over the past five years in Pasuruan District (5.29 tons/ha) was still competitive with the average national rice productivity (5.18 tons/ha) based on the Area Sample Framework survey conducted by Indonesia Central Bureau of Statistic (BPS), while when compared to the average provincial productivity (5.63 tons/ha), the average rice productivity in Pasuruan District was still much lower (BPS 2023b, 2024c).

In 2021, World Agroforestry, the International Center for Research in Agroforestry (ICRAF), introduced climate-smart rice cultivation (CSRC) components in Pasuruan District as a solution to the problem. The low quantity and quality of rice are due to farmers who use conventional or unsustainable farming systems from an ecological perspective. It can lead to decreased farm income from an economic perspective or even total losses due to crop failure. The level of productivity in farming is determined by many factors, such as the allocation of input used by farmers. Farmers cannot use various input allocations according to recommendations or suggestions, so maximum potential cannot be achieved.

Although the CSRC program has produced positive results in demonstration plots and expanded the scale of adoption to farmers, it turns out that many parties still doubt the benefits of implementing the CSRC method. Therefore, this study aims to determine the various determinants of CSRC production adopted by farmers in Pasuruan Regency, especially inputs related to environmental aspects, namely organic fertilizers and organic pesticides.

Two frequently used production functions are Cobb-Douglas and Transcendental Logarithmic (Translog). Research on factors affecting production has been widely conducted using various production function approaches. Adrianto et al. (2016) studied CSRC using the Cobb-Douglass production function using the maximum likelihood estimation (MLE) method. Four of the seven model-building variables, land size, NPK fertilizer, urea fertilizer, organic fertilizer, and labor, are statistically significant production factors, and all have a positive effect. These results align with research conducted by Apriani et al. (2018), which also showed that land size and labor are statistically significant determining variables and have a positive effect. Even more interesting is the research conducted by Burhansyah et al. (2023), which produced a non-significant land size variable, but seeds were statistically significant. Meanwhile, urea fertilizer, NPK fertilizer, and labor variables align with previous research. Priyanto et al. (2022) revealed that land size and seed variables are significant determining factors of production and have a positive effect. Novitaningrum et al. (2020) examined the factors influencing production by dividing fertilizer variables into three elements. N and P fertilizers were shown to be significant, along with five other variables that were shown to be significant, such as land size, seeds, organic fertilizer, and liquid and solid pesticides.

The method of transcendental logarithmic (Translog) production function can also identify farm production factors. Khanal et al. (2018) studied the determinants of rice farming production using the Translog production function approach. Only the capital variable has a statistically significant value and positively affects the four variables tested (land size, labor, and fertilizer). Meanwhile, Salam et al. (2021) obtained land size, fertilizer, and capital variables. Only the capital production factor has a negative effect, and This result contradicts the results of previous studies. Farm capital refers to the use of seeds and pesticides. The statistically significant determinants of land size and fertilizer production have a positive effect and were also obtained by Khatri-Chhetri et al., 2023) in their study. Three other variables (seed, labor, and irrigation) are statistically significant. However, only labor has a negative effect. Hilalullaily et al. (2021) obtained the variables seed, N fertilizer, and land size are significant factors that influence rice farming production.

METHOD

This research was conducted on farmers who adopted climate-smart rice cultivation (CSRC) on the initiative carried out by The 'Rejoso Kita Phase 2' project in Pasuruan District, East Java Province, in 2021. The program was carried out by the World Agroforestry Center or International Center for Research in Agroforestry (ICRAF) in 2018–2023, which wanted to reduce the environmental impact on the downstream area of the Rejoso Watershed, namely increasing the efficiency of water use due to the construction of artesian wells that did not comply with the rules and habits of farmers in cultivating rice with continuous flooded irrigation. The performance of the rice farming system of CSRC adopter farmers is the main focus of this study because there is a change in the composition of farm input use.

The research focused on the performance of rice farming carried out by farmers who implemented CSRC. Cross-sectional data were used in this study with samples that were still alive at the time of the census, had the time availability at the time of data collection, and were willing to be interviewed after going through an explanation process on the informed consent form. The quantity of rice farming inputs was calculated throughout one planting season during the dry season.

The household survey data of farmers came from The World Agroforestry Center (ICRAF) in The 'Rejoso Kita Phase 2' project. The census data collection method was chosen to obtain as many as 168 respondents involved in implementing CSRC. All sample farmers were spread across two sub-districts, namely Winongan and Gondang Wetan, The 'Rejoso Kita Phase 2' project locations. Direct communication techniques through individual face-to-face interviews were chosen in this primary study. A structured digital questionnaire instrument was used during data preparation and collection.

A production function describes the technical relationship that transforms inputs (resources) into outputs (commodities), and a mathematician defines a function as a rule for assigning to each value in one set of variables (the domain of the functions) a single value in another set of variables (the range of the function) (Debertin, 2012). The Cobb-Douglas production function—also called the exponential production function—is often used as a production analysis model because it is simple and more straightforward to see the relationship between inputs and output in the given technology (Cobb & Douglas, 1928).

The Translog production function is an extension of the Cobb-Douglas production function (Christensen et al., 1973; Kumbhakar et al., 2015). The Translog production function is an extension of the Cobb-Douglas production function. Flexibility is the main difference between the Translog production function and the Cobb-Douglas because it does not assume a specific form of production function like the Cobb-Douglas. The Translog production function can provide more accurate and realistic parameter estimates for various industries and production conditions. The Translog production function allows for a more in-depth and comprehensive analysis of how inputs affect output. More complex variations in the relationship between inputs and outputs will likely be captured well. The Translog production function allows for substituting non-proportional and variable input variables. The interaction between inputs through cross-terms can be well described by the Translog production function, which means that changes in one input can affect the productivity of other inputs. The translog production function does not have the assumption of the neoclassical production function, which only applies to the second stage, which is constant returns to scale (CRS). Meanwhile, the Translog production function can capture variable returns to scale.

A total of nine variables were built in the production function model to estimate the determinants of production, including (1) land size (kg); (2) seed (kg); (3) N fertilizer (kg); (4) P fertilizer (kg); (5) K fertilizer (kg); (6) chemical pesticide (liters); (7) organic fertilizer (kg); (8) organic pesticide (liters); and (9) labor (person-days). Fertilizers are broken down based on N, P, and K (Hilalullaily et al., 2021; Novitaningrum et al., 2020). Organic fertilizer is still listed after deducting the N element. The research objectives were analyzed using the Translog production function. The Translog production function of CSRC is denoted as follows (Christensen et al., 1973; Kumbhakar et al., 2015).

$$y = exp\left(\beta_0 + \sum_{j=1}^{p} \beta_j \ln x_j + \frac{1}{2}\sum_{j=1}^{p} \beta_{jj} (\ln x_j)(\ln x_j) + \sum_{j=1}^{p}\sum_{k>j}^{p} \beta_{jk} (\ln x_j)(\ln x_k)\right)$$

with notation after linearization:

$$ln\, y = \beta_0 + \sum_{j=1}^{p} \beta_j \ln x_j + \frac{1}{2}\sum_{j=1}^{p} \beta_{jj} (\ln x_j)(\ln x_j) + \sum_{j=1}^{p}\sum_{k>j}^{p} \beta_{jk} (\ln x_j)(\ln x_k) + \varepsilon$$

y variable is the output, x_j and x_k are the j^{th} and k^{th} inputs, β_0 are constants, β_j is the parameter or coefficient of the first-degree term, and β_{jj} is the parameter or coefficient of the second-degree term, β_{jk} is the parameter or coefficient of the interaction term between the j^{th} and k^{th} inputs, $j = 1,2,\ldots,p$ and $k = 1,2,\ldots,p \quad k > j$, and ε is an error term.

The Translog production function has three terms: the first term is the Cobb-Douglas production function, the second is the second-degree term, and the third is the interaction term. Meanwhile, the error term helps capture variations that affect output that the inputs in the production model do not explain.

In the Translog production function, the number of variables differs from the number of parameters produced. The number of parameters needed can be calculated using the formula as follows.

$$k \times \{(k+1)/2\} + k$$

k is the number of variables. So, in the CSRC production function model, 54 parameters are obtained from the nine variables used. The parameters in the Translog production function can be estimated using the OLS or MLE method, which can be adjusted to the data structure and model used. The Translog production function is more difficult to interpret than the Cobb-Douglass production function. The coefficients in the function obtained cannot directly indicate production elasticity. However, production elasticity can still be presented through further calculations. The elasticity of production to input (x_j) in the Translog production function can be calculated as the partial derivative of the output logarithm to the input logarithm.

$$Ex_j = \frac{\partial\, ln\, y}{\partial \ln x_j} = \beta_j + \sum_{k=1}^{p} \beta_{jk} \ln x_k$$

with Ex_j is elasticity, β_j is the parameter or coefficient of the first-degree term, x_j and x_k are the j^{th} and k^{th} inputs, β_{jk} is the parameter or coefficient of the interaction term between the j^{th} and k^{th} inputs, $j = 1,2,\ldots,p$ and $k = 1,2,\ldots,p \quad k > j$, and ε is an error term

This elasticity shows the percentage change in output due to a percentage change in a particular input. After calculating elasticity, the results can be interpreted to understand how changes in a particular input affect output. An elasticity number greater than one indicates that the input significantly affects the output. Otherwise, an elasticity of less than one indicates a more minor effect. In other words, production elasticity measures the production output response to each input. The greater the value of the production elasticity of input, the more responsive the production output is to the production input. A negative elasticity value in the production function means excessive input production use.

Based on the literature review and research objectives, the relevant hypotheses are (a) land size has a significant and positive effect on rice production, (b) seed has a significant and positive effect on rice production, (c) N fertilizer has a significant and positive effect on rice production, (d) P fertilizer has a significant and negative effect on rice production, (e) K fertilizer has a significant and negative effect on rice production, (f) Chemical pesticides have a significant and positive effect on rice production, (g) Organic fertilizer has a significant and positive effect on rice production, (h) Organic pesticides have a significant and positive effect on rice production, and (i) Labor has a significant and negative effect on rice production.

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RESULTS AND DISCUSSION

Climate-smart rice cultivation (CSRC) maintains high productivity while still paying attention to the environment in the production process. Being environmentally friendly manifests the concepts of climate-smart agriculture, sustainable agriculture, and sustainable development. CSRC components include: The 'Jajar Legowo' planting system planting, alternate wet and drying (AWD)/ intermittent irrigation, balanced fertilization with the support of 'Paddy Soil Test Kit' and 'Leaf Color Charts', and pest and disease control prioritizing organic pesticide for prevention (Leimona et al., 2022).

In implementing CSRC, chemicals are still used, such as fertilizer and pesticide—reasonable concentrations that are allowed—while increasing the use of organic fertilizer and organic pesticide (Yulianingrum et al., 2019). The 'Jajar Legowo' planting system was chosen because it has more benefits than conventional planting distances (Rawung et al., 2021). Intermittent irrigation is also applied because rice plants are not aquatic, even though they require water. Intermittent irrigation is essential in mitigating CH_4 emissions and increasing water productivity (Ayamba et al., 2023; Lampayan et al., 2015). Using inorganic fertilizer in high doses in agriculture causes problems, such as high production costs, reduced farmer income, and dense fertility, and is detrimental to the environment (Sunarpi et al., 2019). Using balanced fertilizer with increased organic fertilizer has a positive impact (Adriani et al., 2022; Saeri & Rahman, 2020). In addition to negatively impacting the environment, reducing the use of chemical fertilizer and increasing organic fertilizer shows more benefits (Athukorala et al., 2023; Li & Yu, 2022).

The average productivity of the CSRC method reached 5.33 tons/ha and it is slightly higher than the average rice productivity for Pasuruan District (**Table 1**).

Table 1. Average CSRC Input Use per Hectare

Description	Number of inputs
Seed (kg)	65.07
N Fertilizer (kg)	45.59
P Fertilizer (kg)	10.92
K Fertilizer (kg)	12.18
Organic fertilizer (kg)	177.90
Chemical pesticide (liters)	1.60
Organic pesticide (liters)	1.86
Hired labor (person-days)	80.02
Family labor (person-days)	148.59

N fertilizer input is used more than other elements. The use of organic fertilizer is much higher than other fertilizer inputs, although it is still below the program recommendation. The use of chemical and organic pesticides is quite balanced. Finally, CSRC still optimizes family labor rather than hiring labor. Land preparation and weeding have the highest percentage, 28% and 24% respectively.

Partial testing (t-test) on the production function is obtained by determining how much the t-ratio or t-count value is against the t-table value. In CSRC, with a degree of freedom of 158 {df=nk=n-(y+x)=168-(1+9)}, the t-table value is 2.61 (α=1%), 1.98 (α=5%), and 1.65 (α=10%). Significance at a certain confidence level will be obtained if the t-count value exceeds the t-table. A gamma coefficient value of one indicates that the independent variable related to gamma has a direct and proportional effect on the dependent variable (**Table 2**) and **Appendix 1** for the full version, which shows that there is no level of variation in rice production caused by differences in technical efficiency and external influences that cannot be controlled by farmers (such as climate, pest and disease attacks, and errors in modeling).

The standard error of 0.00002 indicates the coefficient estimate's uncertainty or variability level. This low value indicates that the gamma coefficient estimate is accurate and reliable. The t-ratio of 55,765.538 results from dividing the coefficient by the standard error (1/0.00002). The t-ratio value indicates that the gamma coefficient is very statistically significant. The sigma-squared coefficient value (σ^2) of 0.105 indicates the variability or uncertainty in the production model. In the Translog production function, this can indicate how much output variation cannot be explained by the input variables. The standard error of 0.010 indicates the level of uncertainty in the coefficient estimate. This value is relatively small, so the Sigma-squared coefficient estimate is accurate. The t-ratio of 10.486 results from dividing the coefficient by the standard error (0.105/0.010). This immense t-ratio value indicates that the Sigma-squared coefficient is very statistically significant. Sigma-squared, which has a coefficient of 0.105 and is statistically significant, means that the combined variance of technical inefficiency and statistical noise is relatively small but significant enough to affect the model results. In other words, the model finds strong evidence that technical inefficiency or statistical noise significantly affects the observed output. This significance also shows that the Translog production model can capture variations in data well, including technical inefficiencies that occur in the production process until the harvest stage.

Table 2 shows that the variables land size, seed, N fertilizer, P fertilizer, chemical pesticide, and organic pesticide have a significant and positive effect at α=1%. These results indicate that increasing the use of these inputs partially (*ceteris paribus*) will increase rice production. Therefore, efforts to increase rice production will be achieved if we pay attention to the use of these inputs. Different results occur in the K fertilizer variable, which has a significant and negative effect at α=1%. Reducing the use of K fertilizer (*ceteris paribus*) will increase rice production. Meanwhile, the variables of land size, organic fertilizer, and labor use are non-significant.

The land size variable is not statistically significant. Khanal et al. (2018) align with the findings but do not align with the findings of previous studies (Khatri-Chhetri et al., 2023; Salam et al., 2021). The finding does not match the hypothesis, but the Translog production function has a second-degree term and interactions with other inputs (**Appendix 1**). The Land size*Land size variable has a significant and negative effect at α=1%, and the results contradict previous studies (Hilalullaily et al., 2021; Khatri-Chhetri et al.,

Table 2. Estimation of the Translog Production Function Model for CSRC

Variables	Parameter	Coefficient	Standard error	t-ratio
Constants	β_0	-9.016***	1.120	-8.049
Land size (ha)	β_1	0.481ns	0.649	0.741
Seed (kg)	β_2	3.223***	0.862	3.740
N Fertilizer (kg)	β_3	2.789***	0.607	4.591
P Fertilizer (kg)	β_4	9.825***	0.734	13.382
K Fertilizer (kg)	β_5	-9.899***	0.719	-13.778
Chemical pesticide (liters)	β_6	1.579***	0.588	2.686
Organic fertilizer (kg)	β_7	-0.010ns	0.044	-0.237
Organic pesticide (liters)	β_8	0.164***	0.055	3.000
Labor (person-days)	β_9	-0.023ns	0.529	-0.044
...	...	...	...	...
Organic pesticide*labor	β_{54}	0.003ns	0.006	0.463
Sigma-squared		0.105***	0.010	10.486
Gamma		1.000***	0.00002	55,765.538

Information:
*** (significant at α=1%),
** (significant at α=5%),
* (significant at α=10%),
ns (non-significant)

2023; Salam et al., 2021). The negative results indicate diminishing returns or decreasing marginal returns from increasing land size, which means that after reaching a certain point, increasing land size no longer provides a proportional increase in output. Conversely, further increases in land size can reduce production efficiency. These results may also indicate that more extensive land management becomes more complex and may require more resources (such as labor and technology) to maintain production efficiency. If not managed well, more extensive land may become less productive. This interpretation indicates the efficient and optimal land management in rice production, especially in the context of climate change adaptation and mitigation.

The seed variable has a significant and positive effect on output, and the results align with the hypothesis and previous studies (Khatri-Chhetri et al., 2023; Novitaningrum et al., 2020; Priyanto et al., 2022). The use of farmer seeds is inefficient because many seeds have been sown but not planted due to the limited planting labor during the same planting season. Not all planting laborers understand the planting techniques used in the 'jajar legowo' planting pattern. In CSRC, the seeds must be given special treatment, such as younger ready-to-plant seedlings and planting 1-2 seedlings per hole. Farmers use excess seeds to anticipate attacks by golden apple snails that damage young rice seedlings. In addition, the habit of farmers of planting more than two seeds per hole is another concern. Unlike previous studies (Khatri-Chhetri et al., 2023; Novitaningrum et al., 2020), this result found nothing interesting in the other seed variables; neither the second-degree term nor other variables interactions were significant.

Regarding fertilizer inputs, CSRC usually uses less fertilizer (efficient) because fertilizer distribution is more even and optimal. In addition, plant nutrient absorption is better because wider planting distances allow for better sunlight penetration and air circulation. N fertilizer has a positive effect, meaning that the land conditions at the research location lack N fertilizer, and this aligns with previous research (Burhansyah et al., 2023; Hilalullaily et al., 2021; Khatri-Chhetri et al., 2023). The findings are consistent with the hypothesis.

The use of N fertilizer by farmers is below the recommended standard, which is around 80-120 kg per hectare. An interesting finding in the second-degree term or the N fertilizer square variable (N fertilizer*N fertilizer) is a significant and negative effect at α=1%, which shows that excessive increase in nitrogen fertilizer use tends to reduce rice productivity. The significant and negative effect of the variable can happen for several reasons, such as excessive use of nitrogen fertilizers, which can cause plant toxicity, inhibit growth, and reduce rice production yields. Excessive application of nitrogen fertilizers can cause nutrient imbalances in the soil, interfering with the absorption of other plant nutrients. This finding contradicts the research of Khatri-Chhetri et al. (2023).

Excessive use of nitrogen fertilizers can cause environmental pollution, such as groundwater and surface water pollution due to nitrogen runoff, which can negatively impact ecosystems and human health. This negative interaction shows an optimal limit in the use of nitrogen fertilizer. Exceeding this limit does not increase production and can harm plants and the environment. Excessive use of nitrogen fertilizer can damage soil structure and fertility long term, ultimately reducing land productivity. Nitrogen fertilizer should be used carefully and correctly to avoid negative impacts on rice production and the environment. A more sustainable and balanced approach to using nitrogen fertilizer is essential to achieve optimal results.

In the interaction with the land size variable, the interaction results obtained the Land size*N fertilizer variable, which had a significant and positive effect. The positive and significant results indicate that increasing nitrogen fertilizer use on more extensive land increases rice productivity, which could happen for several reasons, as nitrogen fertilizer helps improve soil fertility by providing essential nutrients needed by plants for optimal growth, thereby increasing production yields. Using nitrogen fertilizer may be more effective on more extensive land because plants have better access to the nutrients needed for growth. This positive interaction indicates that using nitrogen fertilizer on more extensive land is efficient, thus providing better results than irregular or inappropriate fertilizer use. Although using nitrogen fertilizer can increase production, it is essential to ensure its use is carried out sustainably to avoid negative environmental impacts, such as water and soil pollution.

The input of P fertilizer is identified as having a significant and positive effect, and it aligns with a previous study (Novitaningrum et al., 2020). The finding confirms that the use of P fertilizer is still below the recommendation, namely 20-40 kg per hectare. This condition can occur due to excessive P residue from the previous planting season. The result contradicts the hypothesis of a significant and negative effect because we suspect farmers have less information and application methods for P fertilizer than N fertilizer. Meanwhile, the dose of K fertilizer has a significant and negative effect even though the use of input is below the recommended amount (40-60 kg per hectare). The result is consistent with the hypothesis.

Then, the use of chemical pesticides has a significant and positive effect, and it aligns with previous studies (Khanal et al., 2018; Novitaningrum et al., 2020; Priyanto et al., 2022) through the application of climate change adaptation to rice plants. The finding is consistent with the hypothesis. Otherwise, Salam et al. (2021) and Burhansyah et al. (2023) produced the opposite research findings, which indicate that excessive use of chemical pesticides needs to be reduced in dealing with pests and diseases that attack rice plants.

The interaction variable between land size and chemical pesticides (Land size*Chemical pesticides) shows negative and significant results. These findings are in line with Salam et al. (2021). These results indicate that increasing the use of chemical pesticides on larger sizes tends to reduce rice productivity, which could happen for several reasons, such as excessive use of chemical pesticides on large land sizes, which can damage plants or reduce soil fertility, thereby reducing production yields. Moreover, excessive use of chemical pesticides can cause pests to become resistant, thus decreasing the effectiveness of pesticides and reducing rice production. This negative interaction indicates inefficiency in using chemical pesticides in larger areas. More efficient ways to manage pests and diseases on large land size need must be developed without relying on chemical pesticides.

Excessive use of chemical pesticides can negatively impact the environment, such as water and soil pollution, which can affect land productivity in the long term. These results indicate the need for more sustainable pest management approaches, such as using organic pesticides or integrated pest management (IPM) methods that are more environmentally friendly and can increase land productivity. Increasing chemical pesticides on larger land size do not always increase rice production and may require more efficient and sustainable farm management.

Unfortunately, organic fertilizer is not a significant variable in this study and did not align with the hypothesis. Otherwise, Novitaningrum et al. (2020) and Adrianto et al. (2016) obtained significant results in the organic fertilizer variable. Interesting findings were obtained on the organic fertilizer square variable, which produced a significant and positive effect, indicating that increasing the use of organic fertilizers gradually tends to increase rice productivity. Organic fertilizers help increase soil fertility by providing essential nutrients and improving soil structure, which supports optimal plant growth. Organic fertilizers can increase the activity of beneficial soil microorganisms, which help decompose organic matter and provide nutrients for plants.

The positive interaction on the organic fertilizer variable indicates that organic fertilizers are used efficiently, thus providing better results than irregular or inappropriate use of fertilizers. Using organic fertilizers supports sustainable agricultural practices that increase production and maintain the health of the agricultural ecosystem. Organic fertilizers are more environmentally friendly and can increase soil fertility in the long term. Organic fertilizers can improve the quality of the harvest, which may be more valued in the market and provide additional economic benefits for farmers. The gradual and appropriate use of organic fertilizers can significantly increase rice production. This condition supports more efficient, productive, and sustainable agricultural practices.

The organic pesticides variable has a significant and positive effect. This finding is fascinating in supporting organic pesticides in CSRC input. In the interaction variable with land size (Land size*Organic pesticides), the interaction variable shows a significant and positive result in the Translog production function. The significant and positive result indicates that increasing the use of organic pesticides on more extensive land tends to increase rice productivity, which could be due to several reasons, such as organic pesticides may be more effective in controlling pests without damaging plants or soil, thereby increasing production yields. Moreover, organic pesticides are more environmentally friendly and can improve soil fertility in the long term, contributing to increased productivity. This positive interaction shows that efficiently using organic pesticides in a broader area can provide better results.

The use of organic pesticides supports sustainable agricultural practices that increase production and maintain the health of agricultural ecosystems, which is essential in climate-smart agriculture. Organic pesticides can improve the quality of crops, which may be more valued in the market and provide additional economic benefits to farmers. Organic pesticides on larger land sizes can significantly increase rice production and support more sustainable agriculture.

The labor variable is non-significant, but the interaction variable with land size (Land size*Labor) is interesting to interpret because it is proven negative and significant. These results align with previous studies (Khanal et al., 2018; Khatri-Chhetri et al., 2023; Salam et al., 2021). The significant and negative result indicates that increasing labor use on more extensive land tends to reduce rice productivity, which can occur for several reasons, such as inefficiency in labor use. Labor is not well distributed or does not work optimally, thus reducing productivity. In addition, after a certain point, additional labor no longer provides significant productivity increases and instead decreases efficiency due to coordination or management problems. This result may indicate that there are suboptimal economies of scale in the use of labor on more extensive land. More extensive land may require more sophisticated mechanization or technology than adding more manual labor.

The quality of the labor can also be a factor. If the labor is untrained or inexperienced, increasing the number of workers will not increase or decrease productivity. Inefficient land management can also be a cause. For example, if a larger land size is not managed correctly, adding workers will not effectively increase production output. Increasing labor use on larger land size does not necessarily increase rice production and may require a more efficient and coordinated management approach. Hence, mechanization is essential to develop at stages of farming, such as land preparation, planting, maintenance, harvesting, and post-harvest.

Another interesting interaction variable is P fertilizer*K fertilizer, which has a significant and negative effect. Increasing the use of phosphorus and potassium fertilizers at the same time tends to reduce rice productivity, which could happen for several reasons, such as excessive use or inappropriate combination of phosphorus and potassium fertilizers can cause a nutrient imbalance in the soil, which interfere with the absorption of other nutrients that are also important for plants. In addition, phosphorus and potassium may interact antagonistically in the soil, meaning that increasing one can reduce the effectiveness of the other, thereby reducing plant productivity.

This negative interaction suggests an optimal limit to using phosphorus and potassium fertilizers. Exceeding this limit does not increase production but can also harm plants and the environment. Excessive use of this fertilizer combination can damage soil structure and fertility in the long term, ultimately reducing land productivity. These results indicate the need for more precise and balanced nutrient management. For example, a more in-depth soil analysis may be needed to determine the specific needs of plants and avoid excessive use of fertilizers. Combining these two fertilizers should be done carefully and correctly to avoid negative impacts on rice production and the environment. A more sustainable and balanced approach to fertilizer use is essential to achieve optimal results.

The interaction variable between chemical and organic pesticides (Chemical pesticides*Organic pesticides) is also interesting because it shows positive and significant results. The combination of chemical and organic pesticides tends to increase rice productivity. The combination of chemical and organic pesticides tends to increase rice productivity. Indeed, using organic pesticides is more functional for preventive measures against pest attacks. At the same time, chemical pesticides are designed for pest eradication or extermination. Pesticides can perform both functions, but considering the many negative impacts of pesticides, which are toxic and hazardous chemicals and include persistent organic pollutants (Andesgur, 2019), it is better to use organic pesticides for preventive functions.

The combination can happen because of the synergistic effect where both types of pesticides work together to control pests more effectively than if used separately. Combining chemical and organic pesticides can help reduce the risk of pest resistance to pesticides. Pests that may become resistant to one type of pesticide can be controlled by the other type, thereby increasing pest control effectiveness.

The results of the interaction of the two types of pesticides support an integrated pest management (IPM) approach that combines various pest control methods to achieve better results. Combining chemical and organic pesticides can be part of a more sustainable and environmentally friendly IPM strategy. Combining chemical and organic pesticides may help maintain plant health by reducing pest pressure more effectively so plants can grow better and produce more. Overall, the significant and positive results of the interaction between chemical and organic pesticides in the Translog production function indicate that combining both pesticides can significantly increase rice production. The result supports a more holistic and sustainable pest management approach.

The Translog production function of Climate-Smart Rice Cultivation (CSRC) can be denoted as follows and the complete coefficient results from the total of 54 parameters are in **Appendix 2**.

$$\begin{aligned}\ln Y = {} & -9{,}016 + 0{,}481 \ln X_1 + 3{,}223 \ln X_2 \\ & + 2{,}789 \ln X_3 + 9{,}825 \ln X_4 \\ & - 9{,}899 \ln X_5 + 1{,}579 \ln X_6 \\ & - 0{,}010 \ln X_7 + 0{,}164 \ln X_8 \\ & - 0{,}023 \ln X_9 + 0{,}5 \\ & * -0{,}306 \ln X_1 X_1 + \cdots \\ & + 0{,}003 \ln X_8 X_9 + \varepsilon\end{aligned}$$

The statistically significant variables were calculated further to get the elasticity value by deriving the Translog production function obtained for the variable whose elasticity value is to be sought (**Table 3**).

Table 3. Elasticity of Significant CSRC Variables

Description	Elasticity value
Seed (kg)	0.091
N Fertilizer (kg)	0.097
P Fertilizer (kg)	-0.226
K Fertilizer (kg)	0.231
Chemical pesticide (liters)	0.083
Organic pesticide (liters)	-0.013
LR test	34.210

The LR test value is used to detect the efficient cases in the production process. If the LR test value is above the palm code value, then the FP Translog model does not have an inefficient case. The palm code value at α=5% (0.05) and df=2 is 5.138, and at α=1% (0.05) and df=2 is 8.273. The degree of freedom (df) value is obtained through the number of restrictions that accompany the results of the estimation of the MLE method that has been carried out.

Interpretation of elasticity obtained from various determining factors that influence CSRC rice production in the transcendental logarithmic production function (Translog), namely: a) the elasticity value of rice seed is positive (0.091), which means that if rice seed is increased by 1%, rice production will increase by 0.091%, ceteris paribus; b) the elasticity value of N fertilizer is positive (0.097), which means that if N fertilizer is increased by 1%, rice production will increase by 0.097%, ceteris paribus; c) the elasticity value of P fertilizer is negative (-0.226), which means that if P fertilizer is increased by 1%, rice production will decrease by 0.226%, ceteris paribus; d) the elasticity value of K fertilizer is positive (0.231), which means that if K fertilizer is increased by 1%, rice production will increase by 0.231%, ceteris paribus; e) the elasticity value of chemical pesticide is positive (0.083), which means that if chemical pesticides is increased by 1%, rice production will increase by 0.083%, ceteris paribus; and f) the elasticity value of organic pesticide is negative (-0.013), which means that if organic pesticide is increased by 1%, rice production will decrease by 0.013%, ceteris paribus.

Table 3 explains that the elasticity of CSRC production factors is not elastic. Rice production in current production technology is less responsive to all input use (Hilalullaily et al., 2021). P fertilizer and organic pesticides have been used excessively. Rice production is most responsive to K fertilizer and P fertilizer. These results confirm that using 'Paddy Soil Test Kits' is urgent to support measuring the nutrient status of rice fields in the field with standardization compliance. The results of these measurements can later be the basis for compiling recommendations for fertilizer use according to plant needs. The elasticity of P fertilizer and K fertilizer production is relatively greater than that of N fertilizer. Rice production is more responsive to P fertilizer and K fertilizer than N fertilizer, although the three fertilizer elements are not elastic, and these results contradict the findings of previous studies (Hilalullaily et al., 2021; Novitaningrum et al., 2020).

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

CSRC innovation has a higher average rice productivity level than the average rice productivity in Pasuruan District. So, the innovation introduced did not sacrifice rice productivity, and it can increase farmers' confidence in implementing CSRC innovation technology. The 'jajar legowo' planting system component still faces the constraint of limited labor. The balanced fertilization component becomes essential through the assistance of 'Paddy Soil Test Kit' technology and increasing organic matter to fertilize the soil. The key findings of this study confirm that in the long term, reducing the use of chemical fertilizers and increasing the use of organic fertilizers can improve soil conditions and increase rice production. Applying a combination of organic and chemical pesticide applications is evidence of the conformity of integrated pest control in increasing productivity. These two inputs are complementary, meaning using both inputs together increases output more effectively than if used separately. Meanwhile, the model has not captured the intermittent irrigation component well. Seed, N fertilizer, P fertilizer, K fertilizer, chemical pesticide, and organic pesticide are the determinant factors of CSRC production in Pasuruan District.

RECOMMENDATION

From a policy perspective, these results encourage governments or related institutions to provide more support for efficient and sustainable agricultural practices and avoid uncontrolled land expansion trends in the future. Detailed policy implications can be addressed based on CSRC components, including The 'Jajar Legowo' planting system, which requires mechanization support at the land preparation stage (plowing, sowing, and planting) so that farmers can plant young rice seedlings on time. Chemical fertilizers are excellent when combined with organic fertilizers in the short term. However, in the long term, organic fertilizers must be further encouraged to restore and maintain soil conditions, and chemical fertilizers threaten the sustainability of rice productivity and production. Meanwhile, chemical pesticides and organic pesticides are complementary to obtain optimal production. Research related to the impact of CSRC on farm technical efficiency and income must be carried out to improve study, and it will become additional scientifically evidence-based to improve the CSRC brand and encourage wider adoption of CSRC innovation technology.

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Appendix 1. Estimation of the Translog Production Function Model for CSRC (Complete)

Variables	Parameter	Coefficient	Standard error	t-ratio
Constants	β_0	-9.016***	1.120	-8.049
Land size (ha)	β_1	0.481ns	0.649	0.741
Seeds (kg)	β_2	3.223***	0.862	3.740
N fertilizer (kg)	β_3	2.789***	0.607	4.591
P fertilizer P (kg)	β_4	9.825***	0.734	13.382
K Fertilizer (kg)	β_5	-9.899***	0.719	-13.778
Chemical pesticides (liters)	β_6	1.579***	0.588	2.686
Organic fertilizer (kg)	β_7	-0.010ns	0.044	-0.237
Organic pesticides (liters)	β_8	0.164***	0.055	3.000
Labor (person-days)	β_9	-0.023ns	0.529	-0.044
Land size*Land size	β_{10}	-0.306***	0.095	-3.216
Seed*Seed	β_{11}	-0.153ns	0.137	-1.114
N fertilizer*N fertilizer	β_{12}	-0.157***	0.053	-2.943
P fertilizer*P fertilizer	β_{13}	0.145*	0.081	1.789
K Fertilizer*K Fertilizer	β_{14}	0.042**	0.020	2.165
Chemical pesticides *Chemical pesticides	β_{15}	0.006ns	0.005	1.046
Organic fertilizer*Organic fertilizer	β_{16}	0.003**	0.001	2.515
Organic pesticides*Organic pesticides	β_{17}	0.001ns	0.002	0.515
Labor*Labor	β_{18}	0.027ns	0.072	0.372
Land size*Seeds	β_{19}	0.135ns	0.153	0.885
Land size*N fertilizer	β_{20}	0.305*	0.163	1.863
Land size*P fertilizer	β_{21}	-0.109ns	0.480	-0.227
Land size*K fertilizer	β_{22}	0.227ns	0.471	0.482
Land size*Chemical pesticides	β_{23}	-0.222***	0.073	-3.031
Land size*Organic fertilizer	β_{24}	0.006ns	0.005	1.044
Land size*Organic pesticides	β_{25}	0.031***	0.008	3.741
Land size*Labor	β_{26}	-0.560***	0.146	-3.832
Seed*N fertilizer	β_{27}	-0.135ns	0.111	-1.221
Seed* P fertilizer	β_{28}	-0.425ns	0.475	-0.895
Seed*K fertilizer	β_{29}	0.381ns	0.475	0.801
Seeds*Chemical pesticides	β_{30}	-0.045ns	0.110	-0.410
Seeds*Organic fertilizer	β_{31}	0.007ns	0.007	0.940
Seeds*Organic pesticides	β_{32}	-0.014ns	0.009	-1.492
Seed*Labor	β_{33}	-0.224ns	0.154	-1.456
N fertilizer*P fertilizer	β_{34}	-0.245ns	0.336	-0.730
N fertilizer* K fertilizer	β_{35}	0.198ns	0.331	0.599
N fertilizer*Chemical pesticides	β_{36}	0.028ns	0.035	0.811
N fertilizer*Organic fertilizer	β_{37}	-0.002ns	0.005	-0.429
N fertilizer*Organic pesticide	β_{38}	-0.019***	0.007	-2.819
N fertilizer*Labor	β_{39}	-0.124ns	0.123	-1.010
P fertilizer*K fertilizer	β_{40}	-0.189**	0.091	-2.070
P fertilizer*Chemical pesticide	β_{41}	0.141ns	0.234	0.603
P fertilizer*Organic fertilizer	β_{42}	-0.007ns	0.024	-0.307
P fertilizer*Organic pesticide	β_{43}	-0.012ns	0.020	-0.596
P fertilizer*Labor	β_{44}	-1,460***	0.341	-4,277
K*Fertilizer Chemical pesticide	β_{45}	-0.125ns	0.227	-0.551
K Fertilizer*Organic fertilizer	β_{46}	0.011ns	0.024	0.438
K fertilizer*Organic fertilizer	β_{47}	0.009ns	0.020	0.471
K fertilizer*Labor	β_{48}	1,574***	0.349	4,510
Chemical pesticides*Organic fertilizers	β_{49}	0.002ns	0.004	0.645
Chemical pesticides*Organic pesticides	β_{50}	0.009**	0.003	2.550
Chemical pesticides*Labor	β_{51}	-0.310***	0.093	-3,328
Organic fertilizer*Organic pesticide	β_{52}	0.001*	0,000	1.833
Chemical pesticides*Labor	β_{53}	0.003ns	0.006	0.591
Organic pesticides*Labor	β_{54}	0.003ns	0.006	0.463
Sigma squared		0.105***	0.010	10,486
Gamma		1.000***	0.00002	55,765.538

Information: *** (significant at α=1%), ** (significant at α=5%), * (significant at α=10%), ns (non-significant)

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Appendix 2. Translog CSRC Production Function (Complete Parameters)

$$
\begin{aligned}
\ln Y = {} & -9{,}016 + 0{,}481 \ln X_1 + 3{,}223 \ln X_2 + 2{,}789 \ln X_3 + 9{,}825 \ln X_4 - 9{,}899 \ln X_5 + 1{,}579 \ln X_6 \\
& - 0{,}010 \ln X_7 + 0{,}164 \ln X_8 - 0{,}023 \ln X_9 + 0{,}5 * -0{,}306 \ln X_1X_1 + 0{,}5 \\
& * -0{,}153 \ln X_2X_2 + 0{,}5 * -0{,}157 \ln X_3X_3 + 0{,}5 * 0{,}145 \ln X_4X_4 + 0{,}5 \\
& * 0{,}042 \ln X_5X_5 + 0{,}5 * 0{,}006 \ln X_6X_6 + 0{,}5 * 0{,}003 \ln X_7X_7 + 0{,}5 * 0{,}001 \ln X_8X_8 \\
& + 0{,}5 * 0{,}027 \ln X_9X_9 + 0{,}135 \ln X_1X_2 + 0{,}305 \ln X_1X_3 - 0{,}109 \ln X_1X_4 \\
& + 0{,}227 \ln X_1X_5 - 0{,}222 \ln X_1X_6 + 0{,}006 \ln X_1X_7 + 0{,}031 \ln X_1X_8 - 0{,}560 \ln X_1X_9 \\
& - 0{,}135 \ln X_2X_3 - 0{,}425 \ln X_2X_4 + 0{,}381 \ln X_2X_5 - 0{,}045 \ln X_2X_6 \\
& + 0{,}007 \ln X_2X_7 - 0{,}014 \ln X_2X_8 - 0{,}224 \ln X_2X_9 - 0{,}245 \ln X_3X_4 \\
& + 0{,}198 \ln X_3X_5 + 0{,}028 \ln X_3X_6 - 0{,}002 \ln X_3X_7 - 0{,}019 \ln X_3X_8 \\
& - 0{,}124 \ln X_3X_9 - 0{,}189 \ln X_4X_5 + 0{,}141 \ln X_4X_6 - 0{,}007 \ln X_4X_7 \\
& - 0{,}012 \ln X_4X_8 - 1{,}460 \ln X_4X_9 - 0{,}125 \ln X_5X_6 + 0{,}011 \ln X_5X_7 \\
& + 0{,}009 \ln X_5X_8 + 1{,}574 \ln X_5X_9 + 0{,}002 \ln X_6X_7 + 0{,}009 \ln X_6X_8 - 0{,}310 \ln X_6X_9 \\
& + 0{,}001 \ln X_7X_8 + 0{,}003 \ln X_7X_9 + 0{,}003 \ln X_8X_9 + \varepsilon
\end{aligned}
$$