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# LIMITATIONS OF SUSTAINABILITY CERTIFICATION ON GOOD AGRICULTURAL PRACTICES ADOPTION AMONG CERTIFIED AND NONCERTIFIED OIL PALM SMALLHOLDERS

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## ABSTRACT

Sustainability certifications are often regarded as tools for improving agricultural practices and supporting environmental stewardship among independent oil palm smallholders in Indonesia. However, their effectiveness in driving comprehensive agronomic transformation and improving household income remains debatable. This study examines the effect of sustainability certification on the adoption of Good Agricultural Practices (GAP) among certified and non-certified smallholders in the Philippines. We analyzed data from 64 oil palm smallholders in Simalungun Regency, Indonesia, using comparative and correlation statistical methods. The findings indicate that certification had a limited impact on core agronomic practices, such as fertilization, pruning, and weeding, which remain constrained by structural barriers, including limited technical capacity and financial resources. Certified smallholders exhibited better environmentally focused practices, particularly in reducing the use of hazardous chemicals and adopting sustainable weeding methods, although the differences were not statistically significant. These results suggest that certification programs have been more responsive to external market demands for environmental compliance but have fallen short in facilitating the widespread adoption of productivity-enhancing agronomic practices among smallholders in the region. To achieve environmental sustainability and improved productivity, future certification schemes should be designed to provide stronger agronomic support and balanced incentives. This study provides new insights into the limitations of sustainability certifications in driving comprehensive agronomic improvements, while highlighting their potential to address specific environmental challenges.

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## INTRODUCTION

Palm oil has emerged as an important and strategic commodity, supplying 33% of the global vegetable oil demand. Its production efficiency far surpasses that of other vegetable oil-producing crops, yielding 6–10 times more oil per unit area while requiring 10% less land than rapeseed, sunflowers, and soybeans (UNDP, 2020). Over the past four years, the global demand for palm oil has increased by 8.15%, primarily driven by surging consumption in the food, cosmetics, and renewable energy industries (Oil World, 2023). Palm oil demand is estimated to increase by 33% compared to two decades earlier (Mosnier et al., 2017), driven by global population growth and shifting consumer preferences toward green energy products. Major importing countries, including India (26%), China (16%), the European Union (13%), and Pakistan (8%), are expected to dominate this growing demand (UN Comtrade, 2024). Beyond its critical role in the global supply chain, palm oil significantly contributes to regional economies by generating employment and income for producing countries, particularly in Southeast Asia.

Indonesia is currently the world's leading palm oil producer, contributing approximately 43 million tons (56%) to global production (USDA, 2024). This position emphasizes Indonesia's critical role as a key player in maintaining the stability of vegetable oil supply in international markets. Historical data reveal that while Indonesia's market share has remained stable at 50.8% over the past decade (Oil World, 2023), production growth has failed to keep pace with rising global palm oil demand. In contrast, other palm oil-producing countries, such as Malaysia and Thailand, have enhanced their efficiency and successfully added value through technological innovation and product diversification. Both countries have actively integrated agricultural mechanization and adopted modern technologies in palm oil plantations in recent years. Additionally, circular economic strategies have been implemented by innovatively utilizing biomass byproducts, such as palm kernel shells and empty fruit bunches, to produce renewable energy and organic fertilizers, further enhancing sustainability and productivity. These advancements have enabled both countries to achieve higher yields and strengthen their positions in the global palm oil market. In contrast, palm oil yield in Indonesia has stagnated, largely because of the underperformance of smallholder plantation. Despite managing 6.29 million hectares (40.76% of the total plantation area), smallholders produce only 2.59 tons of crude palm oil (CPO) per hectare annually, leaving a 42% yield gap compared to the optimal potential yield (Monzon et al., 2023). This challenge threatens Indonesia's competitiveness in the global palm oil market and impacts domestic economic resilience, particularly for the 2.52 million smallholders who rely on this commodity as their primary source of livelihood (Central Bureau of Statistics of Indonesia, 2023).

Numerous factors contribute to the poor performance of smallholder plantations in Indonesia, resulting in significant income loss that limits smallholders' ability to meet short-term operational needs and long-term investments, such as replanting programs (Chalil & Barus, 2024). This situation not only impacts economic outcomes but also exacerbates social challenges, such as restricted access to education for smallholders' children and diminished bargaining power against intermediaries. Smallholders are trapped in a cycle of poverty, perpetuated by limited educational attainment and lack of market access, which restricts opportunities for future generations (Bulte et al., 2025).

Restricted credit access also prevents smallholders from adopting yield-enhancing practices, such as balanced fertilization and pest control.

The challenges faced by smallholder oil palm plantations often stem from poor plantation management. Common key issues frequently highlighted include illegitimate planting materials (Woittiez et al., 2015) and suboptimal agronomic practices (Euler et al., 2016), such as imbalanced plant nutrition (Lim et al., 2023; Sugianto et al., 2023), excessively long harvest intervals (de Vos et al., 2023), and irregular pruning and weeding schedules (Monzon et al., 2023). Although intensification through Good Agricultural Practices (GAP) has been promoted as a solution to bridge the yield gap, its implementation among independent oil palm smallholders remains hindered by limited education, resource constraints, and restricted access to basic technologies. Although GAP has been widely adopted by corporate plantations (Popkin et al., 2022), its application at the smallholder level, particularly among independent oil palm smallholders, remains limited (de Vos et al., 2021).

Addressing the yield gap requires a systematic approach that improves agronomic practices and enhances the technical capacity of smallholder farmers. One solution is certification programs, such as the Roundtable on Sustainable Palm Oil (RSPO) certification. While GAP implementation is a core component of the RSPO's sustainability certification, evidence indicates that current practices among certified smallholders often fall short of established standards. Previous studies have assessed GAP adoption among certified independent smallholders; however, these evaluations have typically relied on limited technical variables (de Vos et al., 2021; Euler et al., 2016; Napitupulu et al., 2021). Based on this background, this study aims to extend prior findings by incorporating additional relevant GAP variables to assess certified independent oil palm smallholders' plantation behavior. Furthermore, it will compare GAP adoption between certified and non-certified smallholders to evaluate how far technical progress has been achieved by certified smallholders.

## RESEARCH METHOD

This study adopted the approach outlined by Widiyanti et al. (2020), utilizing primary data collected through semi-structured individual in-depth interviews conducted in Simalungun Regency, North Sumatra (Figure 1). Samples were selected using a systematic random sampling technique based on the smallholder population at the study location. Primary data were collected through face-to-face interviews supported by brief field observations (evidence of pruning, weed control patterns, storage or absence of hazardous chemicals, and harvest residue). The questionnaire covered agronomic practices (fertilization, harvesting interval, pest/disease monitoring and control, pruning, weed management, chemical use), and farmers' income. A total of 64 respondents participated in the study, comprising 30 non-certified and 34 certified independent oil palm smallholders. The certification referenced in this study pertains to sustainability certifications governed by the RSPO. The data analysis method was adapted from the approaches developed by de Vos et al. (2021) and Woittiez et al. (2016) to assess GAP adoption. Eight plantation management practices were evaluated and categorized as fertilization (A1), Harvest Rotation (B1), Pest/Disease Monitoring (C1), Pest/Disease Control Methods (C2), pruning (D1), Weed Management Frequency (E1), Weed Management Methods (E2), and Hazardous Chemical Utilization (F1). Each variable was scored on a scale, with lower scores indicating poorer practices and higher scores indicating better compliance with GAP standards. The scoring ranges for each criterion are presented in Table 1. The scoring range was slightly adjusted in the assessment framework from that of Woittiez et al. (2016), as follows: for variables C2, D1, and F1, there were only four levels, while the rest of the variables had 5-level scoring. For each respondent, all variables were rated according to the level of knowledge applied to palm oil cultivation. Each score will be recalculated to generate a standardized index that accurately reflects the assessed variables.

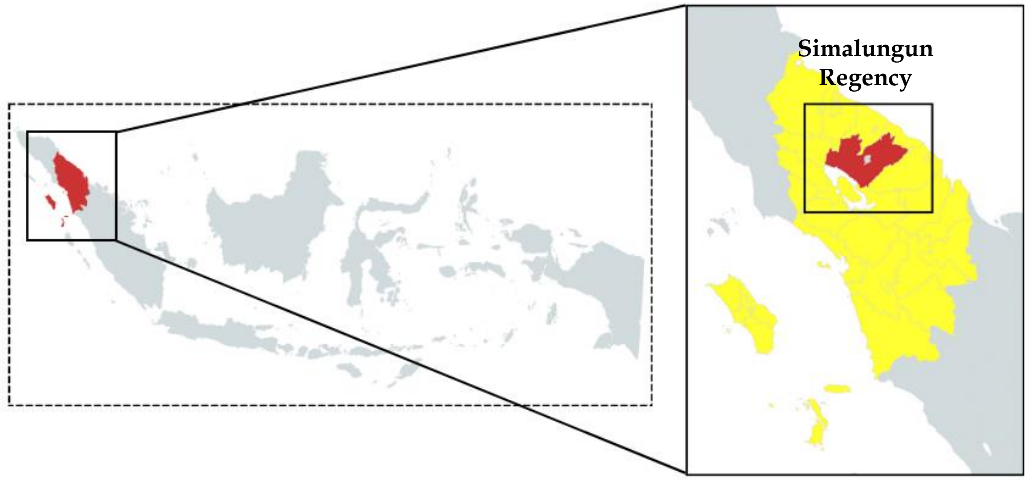


Figure 1.
Research location

The assessment of GAP adoption was presented in the form of an index ranging from 0 to 1, where a score closer to 1 indicated higher conformity with GAP standards, and a lower score reflected poorer adherence. The results were subsequently statistically analyzed to compare plantation management practices between certified and non-certified smallholders. To identify the differences in GAP adoption between these groups, a comparative analysis was conducted using the non-parametric Wilcoxon Rank-Sum Test. This method evaluates the differences in the mean GAP adoption levels and employs a two-tailed hypothesis test with the following hypothesis:

$H_0$: There is no mean difference in the GAP adoption level between smallholder groups.
$H_1$: There is a mean difference in GAP adoption levels between smallholder groups.

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Table 1. Scoring Range of Variables

| Variables | Scoring range | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| A1. Fertilization | No Fertilization | Only 1 or 2 types of fertilizer with a dose < 200 kg/ha | > 200 kg NPK/ha | > 400 kg NPK/ha | > 400 kg NPK/ha + organic fertilizer |
| B1. Harvest Rotation | ≤ 30 days | 21 days | 14 days | 10 days | 7 days |
| C1. Pest/Disease Monitoring | < Once a year | Once a year | Every 6 – 8 months | Every 3 – 5 months | Every month |
| C2. Pest/Disease Control Methods | No control measures | Controlled only by chemical methods | Controlled by chemical and natural methods | Control only by natural methods | - |
| D1. Pruning | < Once a year / every harvest | Once a year | Twice a year | > Twice a year | - |
| E1. Weed Management Frequency | Once every two years | Once a year | Twice a year | Three times a year | Four times a year |
| E2. Weed Management Methods | No weeding | Spraying only the palm circle or frond bases with herbicide | Mechanically cleaning only, the palm circle or frond bases | Spraying the palm circle and harvesting path with herbicide | Mechanically cleaning the palm circle and harvesting path |
| F1. Hazardous Chemical Utilization | No weeding | Use of hazardous chemicals | No use of hazardous chemicals, but still practicing chemical methods | Mechanical weeding | - |

 

We also assessed the relationship between GAP adoption levels and smallholder income using Spearman's rank correlation. This method is appropriate for measuring monotonic relationships between variables when the assumptions of linearity or normal distribution are not met, as is the case with the data used in this study. The formula for calculating Spearman's rank correlation coefficient is as follows:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$

Where: $\rho$ = Spearman's rank correlation coefficient; $d$ = difference between paired rankings; n = number of observations

Data analysis was conducted using Microsoft Excel and Python. Microsoft Excel was employed for managing raw data and generating initial visualizations to facilitate the identification of data patterns. Python, on the other hand, was utilized for more complex statistical analysis and detailed data presentation, leveraging libraries such as Pandas for data processing and Matplotlib and Seaborn for generating more informative and precise visualizations. The combination of these tools enabled a more accurate data presentation and a deeper interpretation of the results.

## RESULT AND DISCUSSION

### Plantation Management Behavior of Certified vs Noncertified Smallholders

Variation in smallholders' behavior reflects high disparities in plantation management practices, resulting in differences in adoption levels. However, certain practices have become standardized, leading to relatively low variability between samples. For instance, in the Harvest Rotation (B1) variable, most smallholders use 14 days as a standard harvest interval. A minority of them (13%), all of whom are non-certified smallholders, opt for approximately 30 days of harvest rotation. The decision to delay harvesting stems from limited landholdings, which reduces potential revenue relative to the high operational costs associated with hiring labor for harvesting. With an average landholding of 0.65 hectares, the returns are often insufficient to justify frequent harvesting. Nevertheless, this decision is considered a trade-off between prioritizing reduced production costs and pursuing higher incomes. Conversely, excessively long harvest rotations lead to new challenges, such as an increased probability of overripe or even rotten fruit, ultimately reducing yields to an average of just 0.95 tons/hectare/month.

Fertilization practices among certified and non-certified smallholders exhibited similar patterns but remained suboptimal to meet the nutritional needs of oil palm plants to achieve their maximum potential (Figure 2). Nitrogen (N) application is the most dominant practice among both certified and non-certified smallholders, although the applied dosage is still below the standard value. A similar issue occurs with potassium (K), which is essential for fruit development and plant resilience; however, its application also falls below the standard dose value. This imbalance is further exacerbated by phosphorus (P) application, which frequently exceeds recommended levels. These findings align with those of Lim et al. (2023), who reported that smallholder oil palm plantations often suffer from excess P and K deficiencies. This nutritional imbalance is caused by poor management due to a lack of information and knowledge, which leads to a decline in productivity. K deficiency can reduce both the quality and quantity of fresh fruit bunches (FFB), whereas an excess of P can trigger nutrient imbalance in the soil. These issues are likely the result of insufficient knowledge among smallholders regarding the specific nutritional needs of their plants, limited access to technical guidelines, and financial constraints that prevent the proportional purchase of fertilizers.

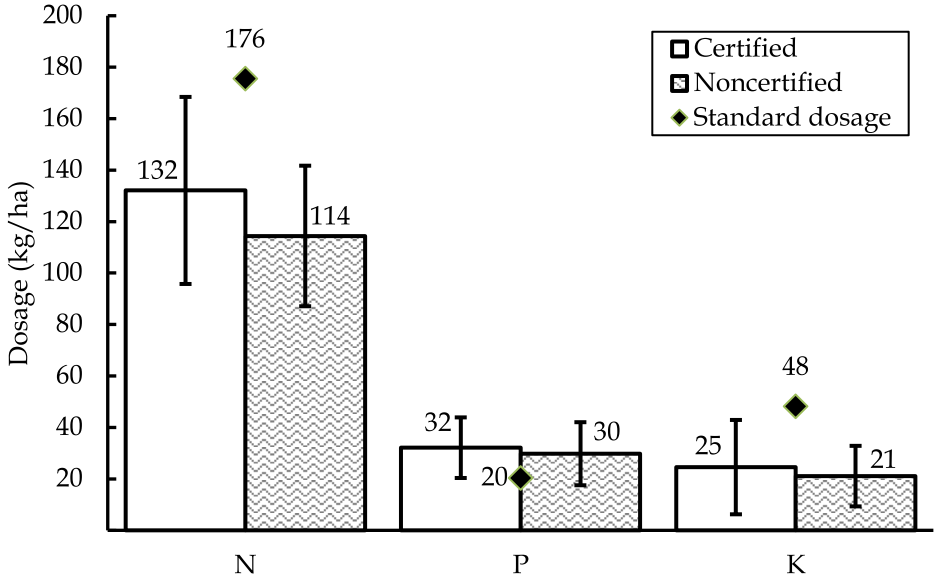


Figure 2.
Fertilization application on oil palm smallholders

Furthermore, pest and disease identification is not regularly conducted by smallholders in the region. Infected plants are often observed, but there are few indications of curative or preventive measures against this disease. The *Oryctes* sp. beetle is the most common pest observed, characterized by perforated fronds and the emergence of new fronds with triangular leaves. In addition, fungal infections caused by *Ganoderma* sp. were identified, leading to Basal Stem Rot (BSR), resulting in early palm death and leaving some areas with no palm stands. In some cases, these areas are repurposed for cultivating economically valuable crops, such as cassava (*Manihot esculenta*), to generate another source of income and maintain their livelihood. Smallholders often attempt to control BSR using traditional methods that lack scientific validation, such as applying mixtures of saltwater, flavor enhancers, and other unconventional substances to soil. The primary reason for these practices is a lack of knowledge regarding pest and disease symptoms, leading to neglect that exacerbates the damage.

Pruning practices among certified and non-certified smallholders are relatively similar. Approximately 30% of smallholders in both groups pruned at intensities that did not adhere to standard procedures. The preference for pruning fronds during every harvest often leads to over-pruning, causing stress to the palm plants. Conversely, another group of smallholders rarely conducts pruning, resulting in under-pruning or excess frond production. Gromikora et al. (2014) highlighted that older palms with excessive fronds are less effective in producing FFB because of difficulties in harvesting and the accumulation of loose fruits. In contrast, heavy pruning increases plant stress and reduces the probability of female flower emergence, negatively affecting the productivity (Prasetyo et al., 2021). Regular front maintenance is essential for preventing plant-stress. However, smallholders often ignore standard procedures because of the high labor costs.

The implementation of weed management techniques highlights a significant disparity in plantation practice. Chemical weeding is more commonly applied by non-certified smallholders (77%) than by certified smallholders (50%), whereas mechanical methods are more prevalent among certified smallholders (27%) than among their non-certified counterparts (10%). A small proportion of smallholders do not engage in any form of weed management, resulting in uncontrolled weed growth around oil palm stands. This difference reflects the impact of education on certified smallholders, particularly in understanding the negative environmental effects of chemical use and the importance of sustainability. Previous studies support these findings, indicating that mechanical weeding not only enhances biodiversity by up to 33%, but also improves financial efficiency by reducing maintenance costs and increasing profitability by up to 12% (Iddris et al., 2023; Lechenet et al., 2017). The higher routine weeding rates among certified smallholders (73% vs. 57%) clearly indicate their greater awareness of weed management as an essential practice for maintaining crop productivity.

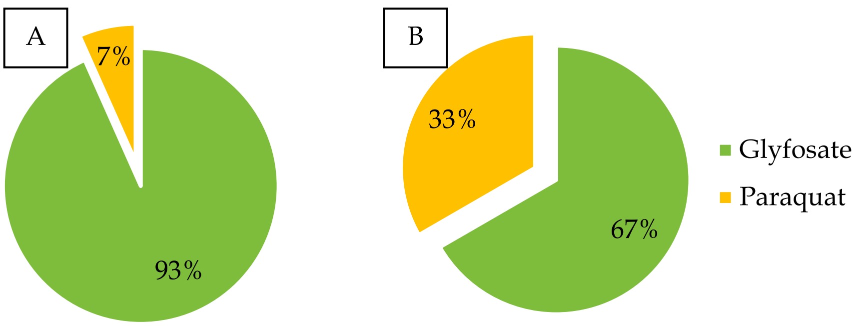


Figure 3.
Utilization of chemical pesticide on certified (A) and noncertified (B) smallholders

In terms of hazardous chemical utilization, certified smallholders differ significantly from non-certified smallholders in hazardous chemical use. . Approximately 33% of non-certified smallholders continued to use paraquat, compared to only 7% of certified smallholders (Figure 3). Paraquat (Paraquat dichloride, $C_{12}H_{14}C_{12}N_2$) is a highly toxic herbicide banned in 67 countries because of its severe health and environmental impacts (Manju et al., 2022; Stuart et al., 2023). Its adverse impact extends to the environmental aspect, contaminating soil and water and posing serious threats to organisms within ecosystems (Chen et al., 2021; Ward et al., 2023). The reduction in paraquat usage among certified smallholders reflects a better understanding of the chemical risks and the necessity for more environmentally friendly pest control approaches. Moreover, Stuart et al. (2023) reported that the effectiveness of paraquat in improving crop productivity was negligible. As an alternative, herbicides containing glyphosate as the active ingredient are recommended because of their superior cost-benefit ratio at specific doses (Hameed et al., 2017). This approach not only supports sustainability but also enhances the long-term economic efficiency of smallholder farmers.

## GAP Adoption Index Among Independent Oil Palm Smallholders

The Mean GAP Index was higher for certified smallholders (0.479) than for noncertified smallholders (0.428) (Figure 4). However, the p-value of 0.0606 indicates insufficient statistical evidence to reject $H_0$, which means that there is no significant difference in the average GAP adoption levels between certified and non-certified smallholders. In this case, certification has not been proven to significantly promote better management practices in most literature. Therefore, the findings do not provide strong evidence that the intervention improved overall GAP adoption in this study sample. The lack of statistical significance may be due to sample size limitations or variability in the implementation of GAP among the participants. Future research with larger sample sizes or alternative study designs is needed to further explore this trend.

The comparative analysis (Table 2) indicates that, overall, there were no statistically significant differences in GAP adoption between certified and non-certified smallholders across most variables, as reflected by p-values of greater than 0.05. The only exception was the Harvest Rotation (B1) variable, which showed a significant difference (p = 0.0417), suggesting that certified smallholders are more likely to adopt proper harvest rotation practices than their non-certified counterparts. For other variables, such as Hazardous Chemical Utilization (F1) and Weed Management Methods (E2), although certified smallholders achieved higher mean scores (0.675 vs. 0.542 for F1 and 0.627 vs. 0.503 for E2), these differences were not statistically significant (p = 0.0589 for F1; p = 0.1096 for E2). This indicates that, despite apparent numerical differences, there is insufficient evidence to conclude that certification consistently leads to higher adoption of these practices among smallholders.

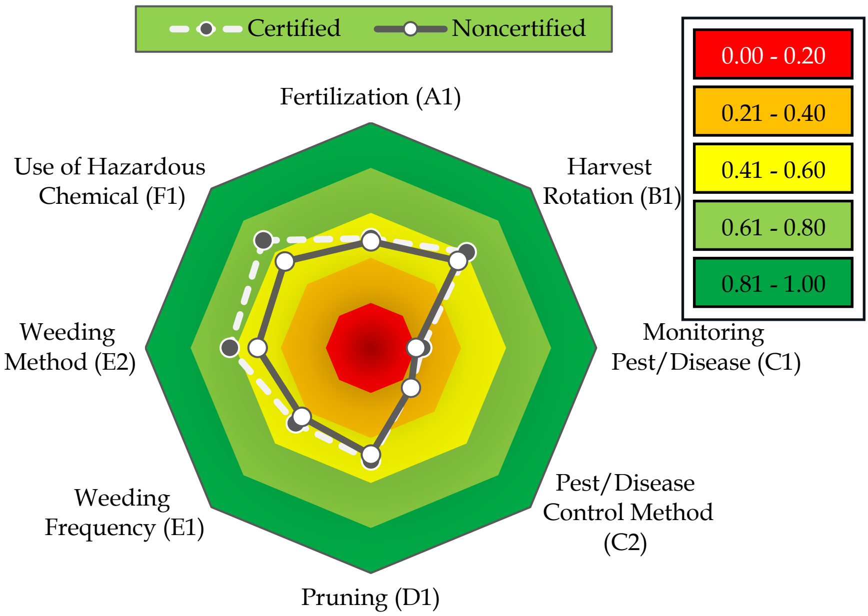


Figure 4.
GAP adoption indeks

Table 2. Comparative analysis result

| Variables | GAP Index | | U-statistic | p-value |
|---|---|---|---|---|
| | Cert | Noncert | | |
| A1. Fertilization | 0.487 | 0.473 | 478.0 | 0.6125 |
| B1. Harvest Rotation* | 0.600 | 0.547 | 510.0 | 0.0417 |
| C1. Monitoring Pest/Disease | 0.227 | 0.200 | 480.0 | 0.4013 |
| C2. Pest/Disease Control Method | 0.250 | 0.250 | 450.0 | 1.000 |
| D1. Pruning | 0.500 | 0.475 | 472.5 | 0.7234 |
| E1. Weeding Frequency | 0.473 | 0.433 | 494.0 | 0.4968 |
| E2. Weeding Method | 0.627 | 0.503 | 554.0 | 0.1096 |
| F1. Hazardous Chemical Utilization | 0.675 | 0.542 | 572.0 | 0.0589 |
| Overall GAP Index | 0.487 | 0.473 | 577.0 | 0.0606 |

Note: *Significant at 5% level

The lack of significant differences in most variables may reflect the persistence of traditional practices, limited access to technical knowledge, or similar resource constraints faced by both the groups. Although certification programs tend to emphasize environmental management, as evidenced by slightly higher scores for environmentally related practices, these improvements have not yet translated into statistically significant changes in most aspects of GAP adoption in this study. Overall, certification has had a limited impact on the widespread adoption of GAP among smallholders, except for certain practices, such as harvest rotation.

## Correlation Between Smallholder's Income dan GAP Adoption

The correlation analysis between each plantation management practice variable and smallholder income is visualized through a Spearman's rank correlation heatmap in Figure 4. The heatmap reveals a strong positive relationship between management practices among both certified and non-certified smallholders. A strong correlation was also observed between the adoption of individual management practices and smallholder income. This underscores the importance of integrated and comprehensive plantation management practices to achieve optimal results and higher economic benefits. In contrast, a partial or limited approach to specific practices can hinder the crop's maximum potential, leading to stagnating smallholder income.

The correlation between each management practice variable and smallholder income was slightly higher among certified smallholders (0.85–0.93) than among noncertified smallholders. Harvest Rotation (B1) and Pest/Disease Control Methods (C2) showed the strongest correlation with income in both groups. In contrast, fertilization (A1) exhibited the weakest correlation with income, likely due to a lack of standardized fertilizer dosages, which prevents crops from reaching their maximum production potential.

The results also revealed a significant difference in income between the two groups of smallholders ($p = 0.0288$), despite the absence of significant differences in plantation-management practices. This indicates that smallholder income structures are not solely influenced by changes in management practices. Smallholders achieve financial stability by diversifying their income sources through on-farm and non-farm activities, which helps to mitigate risks (Syahputra et al., 2024). Diversification is a key strategy, particularly for non-certified smallholders who have limited access to agronomic resources and technical training. Constraints related to farm size and economic capacity often hinder smallholders from fully benefiting from GAP implementation. Although the GAP positively contributes to income, its impact is optimal only when supported by larger farm scales, better access to technology, and financial assistance. This underscores the urgency of more comprehensive policy interventions, including financial incentives, access to appropriate technologies, and more intensive technical support to ensure that GAP implementation significantly improves smallholder income and welfare.

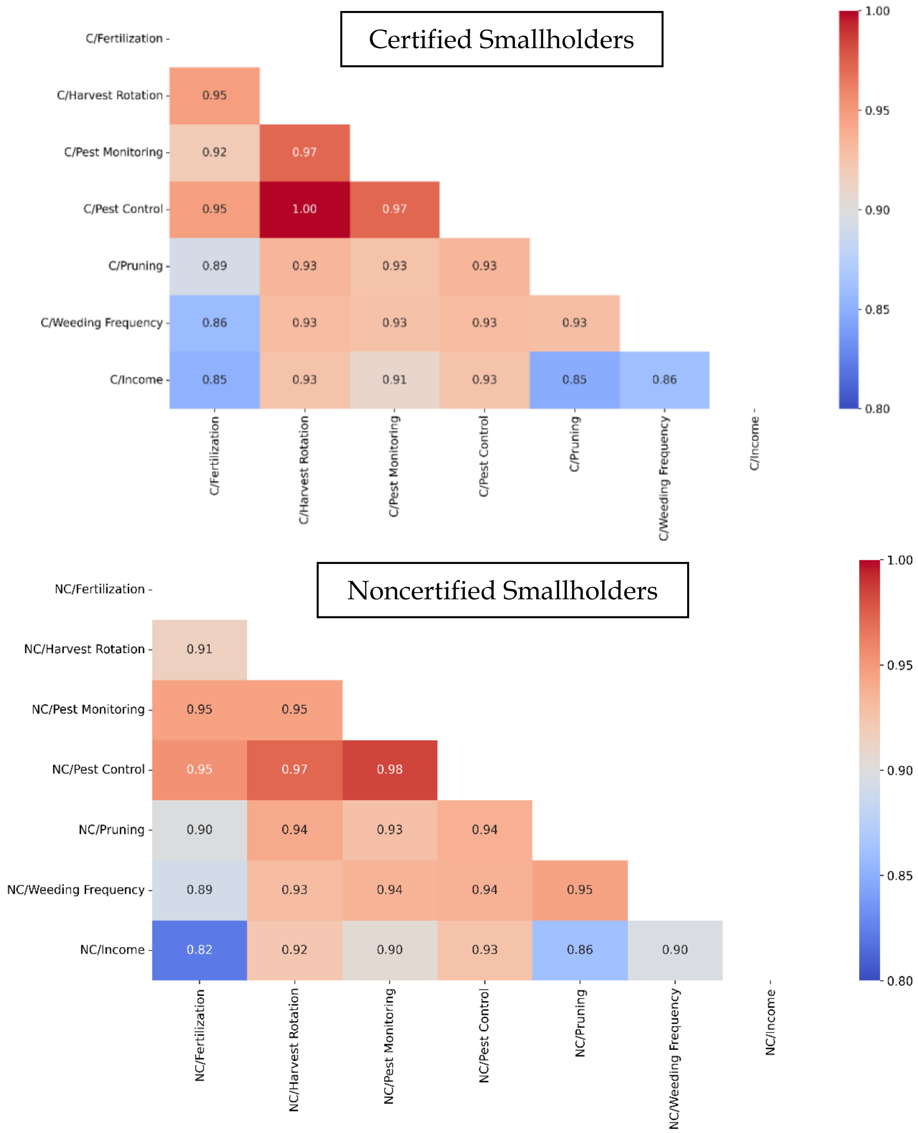


Figure 5.
Heatmap Correlation on Smallholder's GAP and Income

Lestari et al. (2024) stated that the comprehensive implementation of GAP has a significant impact on the productivity and income of oil palm smallholders in Sambas Regency. Enhancing GAP skills among independent smallholders through extension services and training has been shown to improve productivity and income levels. Similar findings were reported by Mohd et al. (2023) in Malaysia, where the adoption of GAP by Malaysian Sustainable Palm Oil (MSPO)-certified smallholders enhanced their productivity and well-being. These findings emphasize the importance of consistent GAP implementation in improving productivity and income for certified and non-certified smallholders. Support in the form of training and technical assistance in GAP adoption is expected to enhance smallholders' competitiveness in an increasingly competitive market.

## External Pressures Shaping Smallholder Practices in Sustainable Palm Oil

One of the primary reasons for the greater improvements in environmental practices among certified smallholders is the strong demand from global consumers, especially in major importing regions such as the European Union. These markets set stringent requirements for palm oil products to be free from environmental issues such as deforestation, hazardous chemical use, and ecosystem degradation. This external market pressure has led certification bodies and cooperatives to prioritize compliance with higher environmental standards during audits and training sessions, often at the expense of productivity-oriented agronomic improvements in the short term.

Several interrelated factors reinforce this environmental focus. First, training provided through certification programs is typically designed to address the most pressing concerns of international buyers, emphasizing environmental compliance rather than productivity. Consequently, smallholders may receive less comprehensive guidance on yield-enhancing practices, leading to gaps in technical knowledge that limit the adoption of productivity-oriented innovation. Second, certification audits frequently prioritize administrative documentation and environmental indicators, while a detailed assessment of actual field-level agronomic practices may be overlooked by them. This approach encourages smallholders to focus on visible compliance measures rather than consistently implementing productivity-improvement techniques.

Furthermore, the incentive structure associated with certification, such as price premiums or access to financial services, is generally more substantial for environmental compliance than for social compliance. Market signals and buyer incentives are directly linked to adherence to environmental standards, as they are the primary concerns of downstream buyers and end-users. Conversely, there is often no direct financial reward or targeted support for smallholders who invest in productivity-enhancing practices unless they contribute to environmental goals. This lack of incentives reduces smallholders’ motivation to adopt agronomic improvements that may require upfront investments or entail additional risks.

Finally, persistent barriers related to the cost and accessibility of key agricultural inputs, such as balanced fertilizers and environmentally friendly pest control options, continue to constrain the capacity of smallholders to agronomically transform. Even when smallholders are aware of best practices, the high cost of certified inputs and limited access to credit or extension services can prevent adoption, especially among independent smallholders with limited bargaining power and economies of scale. Collectively, these factors help explain why certification programs have been more effective in improving environmental practices than in fostering the widespread adoption of core productivity-enhancing ones. Addressing these challenges requires a recalibration of certification design, including the integration of more robust agronomic training, comprehensive field-based audits, targeted incentives for productivity, and improved access to affordable inputs for farmers.

Moreover, recent studies highlight the need for a more integrated approach to certification schemes that balance environmental and productivity objectives of the schemes. Initiatives that combine environmental standards with tailored agronomic support, such as participatory extension services, demonstration plots, and farmer field schools, have shown promise in enhancing compliance and yields among smallholders. Such approaches not only address market demands but also empower farmers to achieve sustainable livelihoods, suggesting that future certification models should evolve into more holistic frameworks.

## CONCLUSION

This study concludes that while certified smallholders show a slightly higher adoption of Good Agricultural Practices (GAP), the difference remains statistically insignificant, suggesting that sustainability certification currently prioritizes environmental compliance over productivity-driven agronomic improvement. The findings reveal that certification has been more responsive to external market pressures and global sustainability mandates—particularly from regions such as the European Union—rather than addressing the core technical barriers that hinder crop performance. A strong correlation between GAP adoption and smallholder income, specifically regarding harvest rotation and pest control methods, underscores the critical economic necessity for integrated management. However, persistent challenges, such as imbalanced fertilization and limited capital, continue to prevent smallholders from reaching their maximum yield potential. Therefore, future certification models must be recalibrated to include robust agronomic training, targeted financial incentives, and simplified fertilization guidelines. Farmer groups should play a more proactive role in bridging these gaps by facilitating knowledge transfer and providing credit schemes to improve nutrient use efficiency. While these results are specific to the institutional and ecological context of Simalungun Regency, they provide vital insights into the need for a more holistic approach that balances ecological stewardship with the economic empowerment of independent oil palm smallholders across Indonesia.

## AUTHOR CONTRIBUTION STATEMENT

[Author 1]: research design, conceptualization, data collection, initial manuscript, methodology, data analysis, addressed reviewer's comments, edited the manuscript; [Author 2]: conceptualization, research supervision, analytical guidance, funding acquisition; [Author 3]: research supervision, analytical guidance, funding acquisition; [Author 4]: data analysis, edited the manuscript, addressed reviewer's comments. All authors reviewed and approved the final version of the article

## DECLARATION OF COMPETING INTEREST

The authors declare that there is no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This declaration is made in the interest of full transparency and to uphold the highest standards of academic integrity.

## ETHIC STATEMENT

This research was conducted in accordance with ethical standards for social science studies involving human participants. Prior to data collection, all respondents provided their voluntary informed consent after being briefed on the study's objectives. To ensure the highest level of privacy, all personal identifiers were removed, and the data were fully anonymized. The authors guarantee that participant confidentiality is strictly maintained and that the information obtained is utilized exclusively for scientific analysis and research purposes.

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