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RESEARCH ARTICLE

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Assessing Labor Utilization Efficiency in Soybean Farming Systems on Acid Sulfate Peatlands

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Abstract

Soybean production on Indonesia's acid sulfate peatlands is constrained by low soil pH, Al/Fe toxicity, and limited mechanization, yielding labor-intensive systems with high physical energy demands. This study quantified labor, energy, and cost flows across field operations (land preparation, planting, maintenance, harvest, postharvest) and converted inputs/outputs to energy equivalents. Total labor reached 652.2 h ha^{-1} (≈91.45 HOK), with planting and weeding dominating human energy use; chemical inputs (fertilizers, pesticides) contributed >80% of external energy. Yield averaged 1,470 kg ha^{-1}, producing 5.29×10^{6} kcal ha^{-1} and an output:input energy ratio of ~3.73. Results indicate that labor efficiency and energy performance can be improved by combining soil amelioration (lime, compost/biochar, inoculants) with simple mechanization for sowing and weed control, thereby reducing hours per hectare and fossil-derived energy without compromising crop care. We recommend extension packages that integrate low-cost tools, organic/biological inputs, and labor-timing guidance to increase returns to labor and lower specific energy per kilogram of soybeans produced on peat-influenced acid sulfate soils.

KEYWORDS
Soybean, Acid sulfate peatland, Labor efficiency, Energy analysis, Biochar, Lime, Rhizobia inoculation, Mechanization, Weed management, Sustainability.

1 | INTRODUCTION

Soybean is a strategic food crop in Indonesia, forming the basis of widely consumed products such as tempeh, tofu, and soy sauce. Yet despite its importance, domestic soybean production has consistently lagged behind demand, forcing the country to rely heavily on imports (Khumairah, 2025). This dependency has created economic vulnerabilities and highlighted the urgent need to enhance soybean productivity on available lands, including marginal soils. Among these marginal soils, acid sulfate peatlands represent both a challenge and an opportunity. Their vast distribution across regions such as Kalimantan and Papua offers land potential for expansion, but severe chemical constraints low pH, high aluminum and iron toxicity, and poor nutrient availability limit yields if not managed carefully (Sulaeman et al., 2024; Widiastuti et al., 2024). Addressing these soil constraints has been the focus of many agronomic interventions. Research has shown that amelioration techniques such as applying lime, compost, or biochar can reduce soil acidity, improve cation exchange capacity, and suppress aluminum toxicity (Manickam et al., 2015; Maharani et al., 2025). Integrated use of organic and biological inputs has also been reported to enhance soybean establishment in acid soils, especially when paired with rhizobial inoculants and sulfate-reducing bacteria (Hanafiah et al., 2022; Simarmata, 2025). While such practices improve soil fertility, their implications for farm-level labor efficiency remain underexplored. Understanding how soil improvements interact with labor requirements is crucial because farmers in these regions often face high production costs with labor representing the largest share of inputs (Setiawan et al., 2025).

Labor efficiency plays a decisive role in the economics of soybean farming. Studies across Java and Sumatra have revealed that inefficiencies in labor use caused by limited mechanization, fragmented landholdings, and low adoption of improved practices are major contributors to the yield gap (Mariyono, 2019; Setiawan & Bowo, 2017). Soybean yields are further compromised when traditional practices demand excess labor during land preparation, weeding, and harvesting. On acid sulfate peatlands, these inefficiencies may be amplified by the additional tasks associated with soil amelioration, making it essential to measure not only productivity but also returns to labor investment.

Recent analyses of soybean farming efficiency suggest that socioeconomic and institutional factors are as important as agronomic ones. For example, education, access to inputs, and the availability of extension support influence both yield and labor productivity (Setiawan et al., 2025; Krisdiana, 2024). Technological innovations such as UAV-based crop monitoring and precision spraying are beginning to emerge in Indonesian agriculture, with potential to reduce labor requirements and improve timeliness of operations (Fikri et al., 2023). However, such innovations are rarely accessible to smallholder farmers cultivating marginal soils. Consequently, practical frameworks for assessing and optimizing manual labor remain urgently needed.

Soybean production in peat-influenced acid sulfate soils has been the subject of agronomic trials exploring organic matter additions and soil amendments. Chotimah et al. (2024) demonstrated that cow manure improved soybean growth and nutrient uptake on inland peatlands, while Lestari et al. (2022, 2024) emphasized the role of integrated organic and biological inputs in sustaining productivity on acidic soils. These studies, while agronomically promising, did not directly assess labor allocation and efficiency. Yet labor is central to the viability of such interventions because practices that increase yields but demand excessive labor may not be sustainable for smallholder households.

Beyond Indonesia, global research also underscores the role of efficient labor use in sustainable cropping systems. Enhanced weathering practices in the U.S. Corn Belt, for example, improved yields while reducing net labor costs by simplifying nutrient management (Beerling et al., 2023). Advances in robotics for soybean seed yield estimation suggest that high-throughput digital monitoring could one day reduce manual labor requirements in developing countries (Feng et al., 2024). Although these technologies are far from being widely deployed in Indonesia, they illustrate the global trend of linking agronomic intensification with labor efficiency metrics.

The present study builds on this context by focusing explicitly on labor utilization efficiency in soybean farming systems on acid sulfate peatlands. It measures labor inputs across different stages of production, including land preparation, planting, weeding, fertilization, and harvesting, while simultaneously assessing yield performance under various soil amendment treatments. By applying efficiency analysis, the research seeks to identify combinations of practices and varieties that maximize returns to labor. Such analysis is crucial in regions where limited access to capital makes optimizing human labor the most practical pathway to improved productivity and profitability.

This work contributes to both science and policy. From a scientific perspective, it integrates agronomic insights on soil amelioration with farm-level economic analysis of labor use—an intersection rarely examined in the literature (Triastono, 2022; Suwardi, 2019). From a policy perspective, the findings provide evidence for designing extension programs that prioritize both soil management and labor productivity, ensuring that farmers receive holistic recommendations. In doing so, the study aligns with Indonesia's broader strategy to reduce dependence on soybean imports by expanding cultivation onto marginal lands in ways that are both agronomically sound and economically feasible (Junaidi et al., 2024).

2 MATERIALS AND METHODS

The study was carried out during the main soybean planting season between May and August in Central Kalimantan, an area characterized by extensive peat-influenced acid sulfate soils that have long been targeted for secondary crop development. Soybean cultivation activities in the field followed standard agronomic practices for the region, including the application of organic materials as soil amendments to improve crop establishment. All stages of production, ranging from land preparation to harvesting and postharvest handling, were closely monitored to document labor use. Labor inputs were recorded in terms of hours of work contributed by household and hired workers for each operation. To complement these measurements, a simple random sampling survey was conducted among participating farmers to obtain representative data on farm-level practices and labor allocation patterns.

The analysis focused on quantifying labor efficiency, energy consumption, and production costs in relation to yield outcomes. Data were collected for each phase of the farming process, including land preparation, planting, fertilization, weeding, pest control, harvesting, and threshing. Human labor inputs were expressed in units of workdays (HOK), with one HOK standardized at 2000 kilocalories of energy expenditure, based on an average daily caloric intake of 3000 kilocalories of which two-thirds was assumed to be allocated to agricultural activities. This approach follows earlier energy accounting frameworks widely used in farm systems research.

To evaluate total energy use, inputs were calculated by summing human labor energy requirements with the caloric equivalents of external inputs such as fertilizers, pesticides, and herbicides. Standard conversion factors were applied, assigning values of 15,946 kilocalories per kilogram of nitrogen fertilizer, 4,127 kilocalories per kilogram of phosphate fertilizer (P_2O_5), and 3,243 kilocalories per kilogram of potassium fertilizer (K_2O). The energy cost for one liter of pesticide or herbicide was estimated at 24,255 kilocalories. For the output side, soybean seed yield was converted into energy equivalents by applying a factor of 4,000 kilocalories per kilogram of seed produced, while the consumable portion was valued at 3,600 kilocalories per kilogram. These coefficients provided a consistent basis for comparing the energy balance of the system.

In addition to energy, financial costs were also analyzed by multiplying total labor hours by the prevailing wage rate in the study area, generating cost-per-hectare estimates for labor. This enabled comparisons of energy-based and monetary efficiency, thereby linking biophysical and economic assessments of farm performance. Production effectiveness was expressed as the ratio of grain yield to labor used, highlighting how efficiently each workday contributed to output.

From these data, several performance indicators were derived. Energy efficiency was measured as the ratio of output energy to input energy per hectare, reflecting the extent to which soybean farming converted invested resources into usable energy. Energy productivity was calculated as grain yield per unit of input energy, emphasizing the relative return of biomass to energy expenditure. Specific energy was assessed as the input energy required to produce one kilogram of soybean, thereby indicating the energy intensity of production. These indicators were analyzed following frameworks used in previous agricultural energy studies, adapted for the specific context of acid sulfate peatland soybean systems.

3 RESULTS

Soybean farming on acid sulfate peatlands in Central Kalimantan relied primarily on human labor, supplemented by limited mechanization. Total labor input reached 652.20 working hours per hectare, equivalent to 91.45 workdays (HOK). This level of labor use was substantially higher than reports from fully mechanized systems. For comparison, soybean farming in the Philippines used approximately 744 hours per hectare, while farming in the United States, with extensive mechanization, required only about 6 hours per hectare (Pimentel, 2009a). In the Lamunti site, the total energy input was calculated at 182,914.26 kilocalories per hectare (765.68 MJ/ha), with an additional 13,817.40 kilocalories supplied by a small tractor.

Land preparation consumed more than 90% of labor in the early stages, largely carried out manually, with only limited assistance from small hand tractors. Land leveling alone accounted for 9,142.85 kilocalories per hectare (4.64% of total energy), while liming and furrow preparation required 8,000–8,500 kilocalories per hectare. Compared with advanced farming systems that rely on full mechanization where energy requirements for tillage typically reach 45–63% of the total (Guruswany et al., 1992) the reliance on manual labor in Lamunti led to disproportionately higher physical energy use.

Table 1: Sequence of activities, labor, and energy inputs in soybean farming on acid sulfate peatlands

No.	Activity	Work time (h/ha)	Energy input (kcal/ha)	Share of labor (%)	Cost (Rp × 1000/ha)
1	Herbicide spraying	9.00	2,571.42	1.30	50.00
2	Land tillage (tractor)	12.00	13,817.40	7.23	700.00
3	Land leveling	32.00	9,142.85	4.64	157.50
4	Liming	15.00	4,285.71	2.18	70.00
5	Making furrows (for organics)	28.00	8,000.00	4.07	140.00
6	Applying organics in furrows	28.00	8,000.00	4.07	140.00
7	Planting	140.00	40,000.00	20.33	700.00
8	Gap filling (replanting)	8.00	2,285.71	1.16	50.00
9	Inorganic fertilization	54.00	15,428.57	7.84	270.00
10	Pest/disease spraying	20.20	5,771.43	2.93	176.50
11	Weeding	110.00	31,428.57	15.97	550.00
12	Hilling	30.00	8,571.43	4.36	150.00
13	Harvesting	68.00	19,428.57	9.81	340.00
14	Postharvest processing	98.00	28,000.00	14.23	490.00
Total		652.20	196,731.66	100.00	3,984.00

Planting was the single most energy-intensive operation, requiring 140 hours per hectare (20.33% of total energy), equivalent to 40,000 kilocalories. This exceeded the 10–14% typically reported in fully mechanized soybean production systems (Guruswany et al., 1992). Limited access to seed drills meant that sowing was performed with simple hand tools, thereby increasing human energy expenditure.

Maintenance operations including fertilization, weeding, hilling, and pest management required significant labor inputs.

Table 2: Labor and energy for maintenance activities in soybean farming on acid sulfate peatlands

No.	Activity	Work time (h)	Workdays (HOK)	Energy input (kcal/ha)
1	Inorganic fertilization	54.00	7.71	15,428.57
2	Organic fertilization	28.00	4.00	8,000.00
3	Weeding	110.00	23.43	31,428.57
4	Hilling	30.00	4.28	8,571.43
5	Pest/disease spraying	20.20	2.88	5,771.43
Total		242.20	42.30	69,200.00

Maintenance accounted for 35.17% of total energy consumption, with weeding alone requiring 31,428.57 kilocalories per hectare. Despite heavy human energy expenditure, the dominant share of input energy (81.73%) came from chemical fertilizers and pesticides. Nitrogen fertilizer contributed the largest proportion, amounting to 48.84% of fertilization energy. This reliance on synthetic inputs mirrors global patterns, though percentages differ by crop; for example, wheat production systems have reported fertilizer accounting for 38.45% of total energy, with nitrogen comprising over 80% of that share (Shahin et al., 2008).

Table 3: Physical inputs, energy, and costs of soybean farming on acid sulfate peatlands

Component	Quantity	Energy input (kcal/ha)	Cost (Rp × 1000/ha)
Soybean seed (kg/ha)	40.0	32,000.00	320.00
Fertilizer N (kg/ha)	22.5	358,763.50	80.00
Fertilizer P_2O_5 (kg/ha)	67.5	275,762.50	525.00
Fertilizer K_2O (kg/ha)	30.0	97,290.00	240.00
Manure (kg/ha)	1000.0	305,000.00	200.00
Pesticide (l/ha)	3.20	77,616.00	600.00
Herbicide (l/ha)	3.00	72,765.00	180.00
Hand tractor (8.5 HP)	–	13,817.40	700.00
Human labor (91.45 HOK/ha)	–	182,914.26	3,284.00
Total Inputs	–	1,418,737.66	6,129.00
Production (kg/ha)	1470.0	5,292,000.00	10,290.00
Production Effectiveness	–	–	16.07

The output energy from dry soybean seed production reached 5,292,000 kilocalories per hectare, corresponding to 1,470 kg/ha yield. With an input energy of 1,418,737.66 kilocalories per hectare, the output-to-input ratio was 3.73:1, indicating a 373% energy return. However, when compared to reported yields of 2,600 kg/ha in the United States, equivalent to 9,360,000 kilocalories per hectare (Pimentel, 2009a), the efficiency of soybean cultivation on these peatlands remained relatively low.

Table 4: Energy input-output ratio in soybean farming on acid sulfate peatlands

Indicator	Unit	Value
Input energy	kcal/ha	1,418,737.66
Output energy	kcal/ha	5,292,000.00
Dry seed yield	kg/ha	1470.00
Energy efficiency	ratio	3.73
Energy productivity	kg/kcal	0.01
Output–input ratio	ratio	3.73 : 1

Harvesting required 68 hours per hectare, equivalent to 19,428.57 kilocalories (9.81% of total input energy). Postharvest processing, including drying, threshing, and storage, accounted for an additional 28,000 kilocalories (14.23%). Despite these inputs, the overall contribution of postharvest operations to total energy remained moderate compared with planting and maintenance.

Chemical energy inputs from fertilizers and pesticides dominated the production system, accounting for more than one million kilocalories per hectare. Pesticide and herbicide use alone required 150,381 kilocalories per hectare, representing nearly 30% of non-labor production costs. This reliance on industrial inputs highlights a major sustainability concern, since much of this energy is derived from non-renewable fossil resources. Substituting with organic amendments and biological pest control could substantially reduce external energy dependence while maintaining crop productivity.

4 | DISCUSSION

The results reveal that soybean farming on acid sulfate peatlands in Lamunti, Central Kalimantan, relies heavily on manual labor, resulting in high physical energy consumption. With 91.45 HOK per hectare and an energy input of nearly 183,000 kcal/ha, the system starkly contrasts with mechanized systems where energy inputs are as low as 6 h/ha (Pimentel, 2009a). This heavy reliance on human labor reflects both the technological constraints and socio-economic context of smallholder farming in peatland environments, where mechanization is limited by infrastructure, cost, and soil characteristics.

The disaggregated energy data highlight pronounced inefficiencies, particularly in labor-intensive operations such as planting (20% of total energy) and weeding (16%). These figures are reminiscent of patterns observed in marginal land systems where labor remains central to operations (Fauzan et al., 2025). The disproportionate energy demands for maintenance underline the need for labor-saving innovations to enhance productivity and reduce energy burdens.

Our energy-output ratio of 3.73 indicates modest performance relative to temperate systems; U.S. soybean systems generate returns well above this level (Pimentel, 2009a). The dominance of chemical inputs contributing over one million kilocalories per hectare in fertilization and pesticide costs mirrors trends in industrial agriculture but raises concerns about sustainability and fossil fuel dependency. A shift toward organic amendments, biofertilizers, or agroecological approaches may help recalibrate energy flows and enhance resilience (Maharani et al., 2025; Fauzan et al., 2025).

Indeed, integrated organic–biological amendments (combined with lime or compost) have shown promise in acid soil amelioration, both in peatland and upland contexts (Lestari et al., 2022; Widiastuti et al., 2024). Reducing reliance on synthetic fertilizers offers dual benefits: lower energy costs and improved soil health. Agroforestry and mulching strategies similarly enhance soil moisture and nutrient retention key complimentary approaches that reduce labor and input strain (Fauzan et al., 2025).

From an efficiency standpoint, the labor-heavy profile observed in this study underscores a significant policy and extension challenge. While advanced technologies like ground robots for yield estimation offer promising routes to reduce labor needs (Feng et al., 2024), their current applicability remains limited for smallholders. Thus, practical interventions that blend low-cost mechanical tools (e.g., improved seeders, weeding aids) with localized organic inputs could improve efficiency substantially.

Furthermore, Indonesia's expansive marginal lands which comprise up to 82% of national territory offer substantial potential for boosting soybean production if labor and soil constraints are addressed (IPB, 2025). Peatland ecosystems also play a critical role in global carbon dynamics, and poorly managed cultivation poses threats to the carbon sink function of peat soils (Mongabay, 2023). Sustainable farming on these soils cannot ignore carbon dynamics or labor sustainability.

Low soybean productivity in Indonesia (circa 1.2 t/ha) and continued reliance on imports highlight structural inefficiencies in the national soybean system (Klumairah, 2025; Perwitasari et al., 2024). Addressing these challenges requires solutions that enhance soil health and labor productivity simultaneously. Technologies like MIGO Bio P 2000 Z microbial fertilizers that reduce chemical reliance and improve yields have demonstrated agronomic and economic promise, though energy-based efficiency effects require further evaluation (Junaidi et al., 2024).

Globally, enhanced weathering of basalt has generated yield improvements for maize and soybean while sequestering carbon (Beerling et al., 2023). While resource-intensive, such strategies point to potential models for regenerative approaches that could combine soil restoration with productivity gains. This underscores the broader need to bridge agronomy, labor economics, and environmental restoration in crafting sustainable soybean systems.

Intercropping and cropping pattern adjustments may offer viable pathways to raise productivity and labor returns. Soybean–maize intercropping systems, for instance, have improved land-use efficiency and income in upland areas (Harsono et al., 2020). While not directly reducing labor inputs, such systems may enhance output per labor unit and diversify risk—a relevant consideration under labor-intensive peatland systems.

Policy and extension approaches must therefore prioritize integrated solutions—facilitating adoption of organic amendments, simple mechanization, improved spacing patterns, and intercrops—to balance labor efficiency and yield outcomes. Financial feasibility studies have shown that improved soybean varieties and cropping systems can be economically competitive, especially when labor is optimized (Krisdiana et al., 2021). This suggests that well-designed extension programs can drive both adoption and efficiency gains.

Importantly, smallholder capacity-building remains fundamental. UAV-based monitoring and yield estimation tools are emerging but face barriers to scale (Fikri et al., 2023; Feng et al., 2024). Extension services should focus on labor-saving, context-appropriate technologies such as hand seeders, microbial inoculants, and mulching materials to improve labor efficiency and sustainability.

The cumulative evidence indicates that enhancing labor utility is not merely a productivity goal it is a critical strategy for sustainability in peatland soybean farming. By reducing energy inputs and improving output per labor hour, these practices can shift the system from high-energy inefficiency toward resilient, green pathways. The subsidy policies, improved varieties, and input support frameworks in place must increasingly account for labor dynamics and energy balance not just yield metrics (Perwitasari et al., 2024; Khumairah, 2025).

Conclusion

This study shows that soybean farming on acid sulfate peatlands is overwhelmingly labor-driven, with planting and weeding dominating human energy use while chemical inputs account for most external energy. Despite modest yields relative to temperate, fully mechanized systems, the energy return (output:input ≈ 3.7:1) demonstrates that performance can be lifted through targeted levers: moderating synthetic fertilizer dependence with organic and biological amendments, introducing simple mechanization for planting and weeding, and refining field operations to reduce work hours per hectare without sacrificing crop care. The evidence indicates that intermediate strategies rhizobial inoculation and lime/compost or biochar for pH and Al toxicity control, hand seeders or jab planters for timelier sowing, and improved weed-control aids can raise returns to labor while curbing fossil-derived energy. In practical terms, extension and policy should pivot from yield-only targets to labor- and energy-aware recommendations, pairing soil amelioration packages with low-cost tools and training. Doing so would move peatland soybean systems toward higher productivity per workday, lower energy intensity per kilogram of grain, and more resilient household economics, while safeguarding the fragile peat environment through reduced reliance on industrial inputs.

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