Agroteknika 9 (3): 576-585 (2026)

AGROTEKNIKA

ISSN: 2685-3450 (*Online*) www.agroteknika.id ISSN: 2685-3450 (*Print*)

Comparative Financial Feasibility of Manual and GPS-Integrated Semi-Autonomous Boat Tractor Ownership in Wetland Agroindustry: Evidence from South Sumatra, Indonesia

Aditya Alphnaori [1], Tamaria Panggabean [*,2], Amin Rejo [2]

[1] Master Program of Agricultural Industrial Technology, Faculty of Agriculture, Sriwijaya University, Palembang, Indonesia
[2] Study Program of Agricultural Engineering, Department of Agricultural Technology, Faculty of Agriculture, Sriwijaya University, Palembang, Indonesia

[*]Corresponding author
Email: tamariapanggabean@fp.unsri.ac.id

Abstract. *Boat tractors are essential for wetland mechanization, but their high cost and the added investment for semi-autonomous navigation raise financial viability concerns for smallholders farming less than 2 ha/year. This study compares manual versus GPS-integrated semi-autonomous boat tractor operation in shallow wetland conditions. Field experiments were conducted on a 0.09 ha plot in South Sumatra using an Agropro FS-28E tractor with a puddler. Technical parameters (operation time, field efficiency, fuel consumption) were measured for both modes. Financial analysis used NPV (6% discount rate), IRR, payback period, and ROI over five years under three annual tillage scenarios: 20, 40, and 60 ha/year. Field efficiency was 100% under manual operation compared with 42% under semi-autonomous operation, while fuel consumption was 1.01 L/ha and 2.40 L/ha, respectively. NPV was IDR -14.3 million (manual) and IDR -21.4 million (semi-autonomous). Manual became feasible at a minimum of 23.4 ha/year, semi-autonomous at ≥ 25.2 ha/year. At 60 ha/year, both were feasible, but manual generated higher NPV (IDR 153.6 vs 142.3 million) and shorter payback (1.5 vs 1.6 years). Under subsidized diesel (IDR 6,800/L) and service tariff (IDR 1.2 million/ha), the semi-autonomous system remains less attractive. A custom hiring service model is more suitable for smallholders with land below the break-even threshold.*

Keywords: *boat tractor, financial feasibility, net present value, semi-autonomous navigation, smallholder farmer, wetland.*

1. Introduction

Wetlands, including swamps and flooded areas, are critical for food security in Indonesia. Boat tractors are designed to operate on low bearing capacity soils using a wide hull that floats on water and soft mud (Xu *et al*., 2023). However, a new boat tractor costs IDR 80-90 million, far beyond the reach of smallholder farmers, who typically own less than two hectares of land (Amrullah *et al*., 2023).

The agricultural workforce in Indonesia is ageing, with 21.2% of farmers aged over 60 years in 2020, while total agricultural labour decreased from 41.3 million in 2005 to 38 million in 2020 (Ngadi *et al*., 2023). Agricultural mechanization is widely regarded as a key strategy (Guan *et al*.,

Diterima: 12 Juni 2026; Disetujui: 6 Juli 2026; TERBITAN AKAN DATANG
https://doi.org/10.55043/agroteknika.v9i3.772.

2023), but adoption rates remain low (Amrullah *et al*., 2023). According to BPS (2024), Indonesia's population reached 278.6 million in 2023, increasing pressure on food production, while agricultural land continues to shrink (Herdiansyah *et al*., 2023).

Semi-autonomous navigation using GPS has the potential to reduce operator fatigue and improve path accuracy (Amagai *et al*., 2023). Integrating such a system increases the initial investment by approximately IDR 4–5 million and may alter field productivity. Previous studies have focused on technical functionality of remote autonomous tractor control systems (Crisnapati & Maneetham, 2022; Handoko *et al*., 2024b). However, empirical evidence regarding the financial feasibility of GPS-integrated semi-autonomous navigation specifically for boat tractors remains limited (weight > 800 kg) operating in shallow wetland mud conditions. A recent study by Handoko *et al*. (2024a) evaluated the financial feasibility of an Android-controlled hand tractor (weight < 200 kg) in wetlands and reported an NPV of IDR 19.9 million and IRR of 28.03%, assuming a field efficiency of 70-75% without empirical verification under actual swamp conditions. Handoko *et al*. (2024b) further demonstrated technical remote control capability, but did not quantify the productivity penalty caused by WiFi latency or calculate the resulting financial impact on operational costs. The present study advances the existing literature in three important ways. First, it directly measures field efficiency and fuel consumption under actual wetland conditions rather than relying on assumed values. Second, it quantifies productivity losses caused by WiFi latency and communication interruptions. Third, it provides the first break-even analysis specifically for semi-autonomous boat tractor ownership. This empirical financial benchmark is essential for smallholder adoption decisions and for guiding technical improvements in control hardware.

Manual operation of small agricultural tractors exposes operators to whole-body vibration and musculoskeletal disorders (Hassan *et al*., 2023; Kongtawelert *et al*., 2022). Remote and semi-autonomous control systems may reduce direct operator exposure to these risks (Handoko *et al*., 2024b), but their adoption depends not only on technical performance but also on acceptable economic returns (Ullah *et al*., 2023).

Farmers are unlikely to adopt a new mechanization technology unless it provides clear technical advantages and acceptable economic returns. Therefore, this study aimed to: (1) compare technical parameters affecting operational costs (field efficiency, work capacity) between manual and semi-autonomous modes; (2) calculate financial feasibility using NPV, IRR, payback period and ROI under different annual tillage area scenarios; (3) determine the minimum tillage area (break-even) that makes each mode viable; and (4) test sensitivity to changes in service tariff and fuel price.

2. Materials and Methods

2.1. Study Site and Period

This field experiment was conducted from September 2025 to April 2026 at the Kayu Agung Experimental Farm, Assessment Institute for Agricultural Technology, Ogan Komering Ilir, South Sumatra, Indonesia. The site is classified as shallow swampland with a standing water depth of 5-10 cm and soft mud layer of 25-40 cm.

2.2. Equipment and Materials

Agropro FS-28E boat tractor (length 2560 mm, width 1940 mm, weight 805 kg, 28 HP diesel engine). Puddler implement (glebeg) with effective working width of 1.58 m. For semi-autonomous mode: 12V DC motor, Raspberry Pi-4 microcontroller, Garmin GPS module, L298N motor driver, 12V battery, Android-based remote control application, 2.4 GHz WiFi link.

2.3. Experimental Design and Technical Measurements

The experimental plot covered 0.09 ha (900 m²). The plot width was set to 19 times the effective working width (19 x 1.58 m), and the length was 30 m. Thus, 19 passes of 30 m each were required to cover the plot. Two operating modes were evaluated: (A) manual control (operator on tractor), (B) semi-autonomous control using Android-based remote control and GPS waypoint navigation. Each treatment was replicated three times. The 0.09 ha plot was selected to ensure precise measurement of all time components (turning, setup, delay, and effective working) under controlled conditions, enabling accurate relative comparison between modes. Field efficiency values reported here are derived from plot-level total operation time and theoretical capacity; they represent comparative performance under experimental conditions rather than absolute large-scale operational efficiency. The 100% value for manual operation reflects the absence of ineffective time within the measured plot passes and should not be interpreted as a general field efficiency benchmark for commercial-scale tillage.

Measured technical parameters included: total operation time, effective work time, and ineffective work time, effective field capacity, theoretical field capacity, and field efficiency. Fuel consumption per hectare was calculated by multiplying the engine fuel consumption rate (2.5 L h^{-1}) by the operating time per hectare.

2.4. Financial Analysis Assumptions

The economic life of the investment was assumed to be five years. The diesel fuel price was assumed to be IDR 6,800 L^{-1}. Discount rate (MARR): 6% per year (based on smallholder credit rate). Annual tillage scenarios: 20 ha, 40 ha and 60 ha (two cropping seasons per year, with multiple farmers or custom hiring). Service tariff for land preparation: IDR 1,200,000 per hectare (local standard). The base boat tractor purchase price was IDR 82,500,000 for both modes. The semi-autonomous mode required an additional IDR 4,500,000 for navigation and control components, resulting in a total initial investment of IDR 87,000,000. Fixed costs consisted of straight-line depreciation, interest on capital and insurance, tax, and garage cost. Tax and garage costs were calculated based on the base tractor value, while the navigation module was included only in depreciation and capital cost calculations. Variable cost per hectare was calculated from field data. Operator wage was IDR 120,000 per person per day, assuming 7 effective working hours per day. Manual mode requires two operators (IDR 144,000/ha); semi-autonomous mode requires one operator (IDR 84,000/ha). Other variable costs (oil and lubricants, maintenance and repairs, spare parts, wheels/tyres) were taken from measured values proportional to operation time.

2.5. Financial Metrics

Net Present Value (NPV) was calculated by discounting annual net cash flows over the five-year project life. Annual net cash flow was calculated by adding depreciation back to annual accounting profit because depreciation is a non-cash cost. The residual value of the tractor, equal to 10% of the initial purchase price, was included as a terminal cash inflow in year 5, while the navigation module was assumed to have zero residual value. NPV was calculated using the following Eq. (1).

$$\mathrm{NPV}=(-I_0)+\sum_{t=1}^{n}\left(\frac{NCF_t}{(1+i)^t}\right)+\left(\frac{RV}{(1+i)^n}\right) \tag{1}$$

Where I_0 is the initial investment, NCF_t is the annual net cash flow in year t, i is the discount rate, RV is the residual value, and n is the project life. The discount rate used in this study was 6% per year. An investment was financially feasible when NPV > 0.

Internal Rate of Return (IRR) was defined as the discount rate that makes NPV equal to zero. IRR was estimated by interpolation between two discount rates that produced positive and negative NPV values. The investment was considered feasible when IRR exceeded the MARR of 6%.

Payback Period (PBP) was computed as the time when cumulative discounted cash flow equals the initial investment.

Return on Investment (ROI) was calculated based on annual accounting profit after deducting fixed and variable costs, including depreciation.

$$\mathrm{ROI}=\left(\frac{\text{Average annual net profit}}{\text{initial investment}}\right)\times 100\% \tag{2}$$

2.6. Break-Even and Sensitivity Analysis

The minimum annual tillage area required for NPV = 0 was calculated by linear interpolation between the nearest scenarios that produced negative and positive NPV values (20 and 40 ha/year for both modes). Sensitivity analysis was performed for the 40 ha/year scenario under service tariff changes of ±20% and fuel price increase of 15%.

3. Results and Discussion

3.1. Technical Parameters Affecting Operational Costs

Table 1 summarizes the field measurements and recalculated variable cost inputs. Data in Table 1 are presented as means of three replicates ± standard deviation. No significant difference in forward speed was observed between the two operating modes (4.36 m/s). However, semi-autonomous mode experienced response delays (1.96-2.17 s), intermittent WiFi disconnections, and pre-operational setup time of 300 seconds per session. Consequently, field efficiency decreased to 42% compared with 100% for manual operation, and operation time per hectare increased 2.38-fold, from 0.403 h/ha to 0.961 h/ha. Consequently, fuel, lubricant, maintenance, and labour costs increased substantially. An independent t-test confirmed that field efficiency, operation time per hectare, and fuel consumption differed significantly between modes ($p < 0.05$ for all parameters).

Table 1. Technical parameters of boat tractor operation (mean of three replicates ± SD)

Parameter	Manual	Semi-autonomous
Forward speed (m/s)	4.36 ± 0.05	4.36 ± 0.05
Effective working width (m)	1.58 ± 0.0	1.58 ± 0.0
Theoretical field capacity (ha/h)	2.48 ± 0.03	2.48± 0.03
Total operation time for 0.09 ha (h)	0.0363 ± 0.0011	0.0865 ± 0.0072
Effective field capacity (ha/h)	2.48 ± 0.08	1.04 ± 0.09
Field efficiency (%)	100 ± 0.0	42 ± 3.6
Operation time per hectare (h/ha)	0.403 ± 0.012	0.961 ± 0.08
Fuel consumption per hectare (L)*	1.01 ± 0.03	2.40 ± 0.2
Operator cost per hectare (IDR)**	144,000 ± 0.0	84,000 ± 0.0
Other variable costs per hectare (IDR)***	52,800 ± 1,600	128,000 ± 10,700

*Calculated from engine fuel consumption (2.5 L/h) x hours per hectare. **Manual: 2 persons x IDR 120,000/day, converted using hours per hectare; semi-autonomous: 1 person ***Includes oil/lubricants, maintenance and repairs, spare parts, wheels/tyres (proportional to operation time).

Note: Field efficiency was calculated based on plot-level total operation time and theoretical field capacity derived from the measured forward speed. The 100% value for manual operation reflects the controlled plot-scale calculation and should be interpreted as a relative comparison under the experimental conditions rather than a general field efficiency value.

3.2. Annual Cost under Different Tillage Areas

Table 2 presents the financial feasibility of manual and semi-autonomous boat tractor ownership at 20, 40, and 60 ha/year. The break-even area (NPV = 0) was approximately 23.4 ha/year for manual and 25.2 ha/year for semi-autonomous operation, based on interpolation between the 20 and 40 ha/year scenarios.

Table 2. Financial feasibility at 20, 40, and 60 ha/year.

No.	Parameter	Manual			Semi-autonomous		
		20 Ha	40 Ha	60 Ha	20 Ha	40 ha	60 ha
1	**Expenditure**						
a	Fixed costs per year						
	Tractor purchase price (IDR)	82,500,000	82,500,000	82,500,000	82,500,000	82,500,000	82,500,000
	Navigation module price (IDR)	-	-	-	4,500,000	4,500,000	4,500,000
	Tractor depreciation (5 years, 10% residual) (IDR)	14,850,000	14,850,000	14,850,000	14,850,000	14,850,000	14,850,000
	Navigation module depreciation (5 years, 0% residual) (IDR)	-	-	-	900,000	900,000	900,000
	Interest on capital and insurance (6% of average investment) (IDR)	2,722,500	2,722,500	2,722,500	2,857,500	2,857,500	2,857,500
	Tax (2%) (IDR)	1,650,000	1,650,000	1,650,000	1,650,000	1,650,000	1,650,000
	Garage (1%) (IDR)	825,000	825,000	825,000	825,000	825,000	825,000
	Total fixed cost per year (IDR)	**20,047,500**	**20,047,500**	**20,047,500**	**21,082,500**	**21,082,500**	**21,082,500**
b	Variable Costs						
	Fuel (1.01 L/ha for manual, 2.40 L/ha for semi-autonomous) (IDR)	137,360	274,720	412,080	326,400	652,800	979,200
	Maintenance and repairs (IDR)	1,056,000	2,112,000	3,168,000	2,560,000	5,120,000	7,680,000
	Operator (IDR)	2,880,000	5,760,000	8,640,000	1,680,000	3,360,000	5,040,000
	Total variable cost per year (IDR)	4,073,360	8,146,720	12,220,080	4,566,400	9,132,800	13,699,200
c	**Total cost per year (IDR)**	**24,120,860**	**28,194,220**	**32,267,580**	**25,648,900**	**30,215,300**	**34,781,700**
2	**Revenue**						
	Service tariff per ha (IDR)	**1,200,000**	**1,200,000**	**1,200,000**	**1,200,000**	**1,200,000**	**1,200,000**
	Annual revenue (IDR)	**24,000,000**	**48,000,000**	**72,000,000**	**24,000,000**	**48,000,000**	**72,000,000**
3	**Annual profit (IDR)**	**(120,860)**	**19,805,780**	**39,732,420**	**(1,648,900)**	**17,784,700**	**37,218,300**
4	**NPV (5 years, 6% discount rate) (IDR)**	**(14,290,624)**	**69,647,633**	**153,585,889**	**(21,436,157)**	**60,425,236**	**142,286,629**
5	**IRR %**	**(0.23)**	**32.53**	**60.52**	**(3.02)**	**28.18**	**54.57**
6	**Payback Period (years)**	**5.6**	**2.4**	**1.5**	**6.2**	**2.6**	**1.6**
7	**ROI (%)**	**(0.15)**	**24.01**	**48.16**	**(1.9)**	**20.44**	**42.78**
8	**Feasible?**	**No**	**Yes**	**Yes**	**No**	**Yes**	**Yes**

Break-even area manual = 23.4 ha/year, and semi-autonomous = 25.2 ha/year.

3.3. Sensitivity Analysis (at 40 ha/year)

Table 3 shows NPV sensitivity to changes in service tariff and fuel price. Under the baseline scenario, manual operation gave a higher NPV than the semi-autonomous mode. A 20% tariff reduction lowered manual NPV to IDR 29.2 million and semi-autonomous NPV to IDR 20.0 million, indicating that the semi-autonomous mode is more vulnerable to tariff cuts. A 15% fuel price increase had a relatively small effect because fuel represents a minor share of variable costs.

A switching value analysis was performed to determine the conditions under which semi-autonomous operation would achieve NPV parity with manual operation at 40 ha/year. Holding all other parameters constant, the service tariff would need to increase from IDR 1.2 million/ha to IDR 1.52 million/ha (a 26.7% increase) for semi-autonomous NPV to equal manual NPV. Alternatively, fuel consumption per hectare for the semi-autonomous mode would need to decrease from 2.40 L/ha to 1.25 L/ha (a 48% reduction) to achieve parity, assuming the current tariff. This indicates that while tariff increases could partially compensate for lower efficiency, substantial technical improvement in fuel efficiency or communication latency is the more realistic pathway to competitiveness.

Table 3. Sensitivity of NPV (IDR million) at 40 ha/year

Scenario	Manual	Semi-autonomous
Baseline (tariff IDR 1.2 M/ha, fuel IDR 6,800/L)	69.6	60.4
Tariff -20% (IDR 960,000/ha)	29.2	20.0
Tariff +20% (IDR 1,440,000/ha)	110.1	100.9
Fuel price +15% (IDR 7,820/L)	69.5	60.0

3.4. Discussion

The semi-autonomous mode achieved a field efficiency of 42%, lower than manual operation under the observed wetland conditions. This lower performance was associated with response delays, intermittent WiFi disconnections, and additional pre-operational setup time. Handoko *et al*. (2024b) reported higher field efficiencies for an Android-controlled hand tractor, but direct comparison is limited by differences in machine size, plot size, wetland depth, control architecture, and communication robustness. These results suggest that reliable low-latency communication and robust control hardware are essential for improving the operational performance of semi-autonomous tractors in wetland environments (Zhang *et al*., 2021; Cundar *et al*., 2023).

The break-even areas in this study differ from those reported by Handoko *et al*. (2024a), mainly because of differences in fuel price assumptions, field efficiency and machine type. The present results should be interpreted as a case-specific financial assessment under the assumed subsidized fuel price. Under higher fuel prices, both modes would be less feasible, although manual operation would likely maintain its advantage due to lower fuel consumption per hectare.

The finding that semi-autonomous navigation is not yet financially competitive under real-world field conditions (low efficiency, higher variable costs) has important implications. The additional investment of IDR 4.5 million for GPS and control components is only justified if field efficiency can be raised to at least match manual mode, or if fuel consumption per hectare can be reduced. Technical improvements should target: (1) low latency communication (LoRa or 4G instead of WiFi), (2) proportional actuators for smoother steering, (3) vibration proof permanent mounting of electronics, and (4) fail-safe mechanisms (Handoko *et al*., 2024b; Mottalib *et al*., 2024).

Given that the average smallholder farmer in Indonesia cultivates less than 2 hectares (Amrullah *et al*., 2023), individual ownership of a boat tractor (manual or semi-autonomous) is unlikely to be financially feasible. A more realistic pathway is a custom hiring service model, in which a service provider owns the tractor and provides land preparation services to multiple farmers. Under this model, a single tractor can cover 40-60 ha/year, making manual ownership viable. Semi-autonomous navigation would require further technical maturation before it can compete (Lowenberg-Deboer *et al*., 2021).

4. Conclusion

The semi-autonomous mode showed lower operational performance than the manual mode under the observed field conditions, with field efficiency of 42% versus 100% and fuel consumption of 2.40 L/ha versus 1.01 L/ha. Based on the financial assumptions used in this study, manual boat tractor ownership became financially feasible at approximately 23.4 ha/year, whereas semi-autonomous ownership requires approximately 25.2 ha/year. At 60 ha/year, both modes are feasible, but manual operation generated higher NPV (IDR 153.6 million vs 142.3 million) and shorter payback period (1.5 vs 1.6 years). Semi-autonomous navigation was found to be less economically attractive due to lower field efficiency and higher variable costs per hectare. For farmers cultivating areas below the break-even threshold, particularly smallholders with less than 2 ha, a custom hiring service model is more appropriate than individual ownership. Further improvements in communication latency, control reliability, and vibration resistance are required before semi-autonomous navigation can become financially competitive. Future studies should validate the system across different wetland types, machine models, and improved control architectures.

Abbreviations

BPS	Badan Pusat Statistik (Statistics Indonesia)
GPS	Global Positioning System
Ha	Hectare

IDR	Indonesia Rupiah
IRR	Internal Rate of Return
MARR	Minimum Acceptable Rate of Return
NPV	Net Present Value
PBP	Payback Period
ROI	Return on Investment
WiFi	Wireless Fidelity

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Aditya Alphanori: Investigation, data curation, writing original draft. **Tamaria Panggabean:** Conceptualization, methodology, validation, writing review and editing, supervision. **Amin Rejo:** Conceptualization, funding acquisition, project administration, resources, supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was funded under BIMA Research Program, Fundamental Research Scheme (PF), administered by the Ministry of Higher Education, Science, and Technology, Directorate General of Research and Development of the Republic of Indonesia. The project was carried out under Contract Agreement Number 0029/UN9/SK.LPPM.PT/2025, chaired by Amin Rejo. The authors express their sincere appreciation to the Ministry for the support that enabled the implementation and completion of this research. The authors thank the Kayu Agung Experimental Farm, Assessment Institute for Agricultural Technology, South Sumatra, for providing the boat tractor and field facilities.

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