Supplementary Materials

Socio-Economic Benefits of Different Indonesian Crops: Opportunities for Sago Starch in Bioplastic Development

Sustainability

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Section A. Oil palm yield

Table S1. Oil palm yield normalization factor based on [1].

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Oil palm yield factor	0.00	0.00	0.35	0.61	0.73	0.86	1.07	1.21	1.29	1.29	1.29	1.29	1.29

Year	14	15	16	17	18	19	20	21	22	23	24	25
Oil palm yield factor	1.24	1.19	1.15	1.10	1.05	1.01	0.96	0.92	0.85	0.80	0.76	0.71

Table S2. Normalized baseline annual yield of oil palm FFB (kg/ha) in this study.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Oil palm yield factor	0	0	5,191	9,119	10,922	12,746	16,012	18,022	19,165	19,165	19,165	19,165	19,165

Year	14	15	16	17	18	19	20	21	22	23	24	25
Oil palm yield factor	18,485	17,701	17,175	16,351	15,651	15,012	14,332	13,724	12,590	11,931	11,292	10,612

Section B. Social cost of carbon dioxide (SC-CO_2) calculation

We used the Tier 1 2019 refinement to the IPCC 2006 formula [2] to calculate direct and indirect GHG emissions and Hooijer et al. [3] formula to calculate CO_2 emission from peat oxidation. For mineral soil, emissions were estimated based on the fertilizer applied, whereas for peat soil, the calculations considered both fertilizer applications and peat water levels. Two emissions were considered in fertilizer application: nitrous oxide (N_2O) and carbon dioxide (CO_2), which were then converted into CO_2 equivalent (CO_2-eq) using a 100-year GWP horizon. The equations used in our calculations are as follows:

Direct emissions:

$$N_2O - N = F_N * EF_N \quad (B.1)$$

$$CO_2 - C = M_{\text{Urea or Dolomite}} * EF_C \quad (B.2)$$

where N_2O-N is N in N_2O emission (kgN/year), F_N represents the quantity of N in manure or synthetic fertilizer (kgN/year), EF_N represents N emission factor per kg N (kgN_2O-N/kgN), CO_2-C is C in CO_2 emission (kgC/year), M_{Urea} and $M_{Dolomite}$ represent the quantity of urea and dolomite fertilizers applied (kg/year), and EF_C represents C emission factor per kg urea or dolomite (kgC/kg urea or dolomite);

Indirect emission:

$$N_2O_{(ATD)} - N = F_N * NFrac_{ATD} * EF_{N-ATD} \quad (B.3)$$

$$N_2O_{(LEACH)} - N = F_N * NFrac_{LEACH} * EF_{N-LEACH} \quad (B.4)$$

where $N_2O_{(ATD)}$-N is N in N_2O emission from atmospheric N volatilization and deposition (kgN/year), $NFrac_{ATD}$ represents the fraction of N volatilized as NH_3 and NOx from manure or synthetic fertilizers (kgN/kgN), $EF_{N\text{-}ATD}$ represents N emission factor for atmospheric volatilization and deposition (kgN_2O-N/kgN), $N_2O_{(LEACH)}$-N is N in N_2O emission from N through leaching and runoff (kgN/year), $NFrac_{LEACH}$ represents fraction of N leached through leaching and runoff (kgN/kgN), and $EF_{N\text{-}LEACH}$ represents N emission factor from N leaching and runoff (kgN_2O-N/kgN);

CO_2 from peat oxidation:

$$CL = 21 - 69 * WD \quad (B.5)$$

where CL is annual CO_2 loss (tCO_2-eq/ha), and WD represents the peat water depth below the surface (-m, negative).

The values of the variables used in CO_2 emissions calculations are presented in Table S3.

Table S3. Values of the variables in the calculations.

Variable	Value	Note	Reference
F_N			
Poultry manure	3.70%	Fresh	[4]
Rice husk	0.40%	Fresh	[4]
Urea	0.46 kg	Per kg urea	Fertilizer's label
NPK	0.15 kg	Per kg NPK	Fertilizer's label
EF_N			

Manure	0.029	Mixed	[2]
Urea and NPK	0.016	Wet climates	[2]
EF_C			
Urea	0.2	Default value	[2]
Dolomite	0.13	Default value	[2]
$NFrac_{ATD}$			
Manure	0.21	Default value	[2]
Urea and NPK	0.11	Default value	[2]
$EF_{N\text{-}ATD}$	0.14	Wet climates	[2]
$NFrac_{LEACH}$	0.24	Default value	[2]
$EF_{N\text{-}LEACH}$	0.011	Default value	[2]
WD	0.4		Regulation 57/2016
Conversions			
N_2O	N_2O-N * (44/28)		Molecular weight
CO_2	CO_2-C * (44/12)		Molecular weight
CO_2-eq	N_2O * 265	GWP 100-year	[5]

Section C. Fertilizer and labor inputs for sago and oil palm optimum yield scenarios

This section outlines the scenarios for increasing the productivity of sago and oil palm to 50% (O50) and 90% (O90) of their optimum possible yields, assuming that maximum fertilizer inputs will result in 90% of the optimum yield. For sago cultivation, the scenarios include both newly planted sago (new O50 and new O90) and existing mature sago (mature O50 and mature O90). For oil palm, only the new O90 scenario is considered, as current production already exceeds 50% of its potential optimum yield.

We estimated the annual sago palm nutrient requirement based on the ideal 278 sago clusters per ha [6]. Jong and Flach [7] estimate the nutrition uptake of sago planted on peatland from age 1 YAP to 12 YAP, at its harvesting time. The nutrient consists of N, P, K, Ca, and Mg. In our new sago O90 scenario, we adjusted this nutrient information to an eight-year period, following our sago harvesting time, by distributing the nutrient uptake of the first four years evenly across this timeframe. The total nutrients required per year were then converted into marketed fertilizers, i.e., urea (46% N), rock phosphate (28% P_2O_5), muriate of potash (60% K_2O), and dolomite (30% CaO and 22% Mg). The respective market prices per kg of these fertilizers were EUR 0.48, EUR 0.27, EUR 0.06, and EUR 0.09. The annual fertilizer requirement of the new sago O90 scenario is presented in Table S4.

Table S4. Annual fertilizer requirement per ha for the new sago O90 scenario.

YAP	Urea	Rock Phosphate	MOP	Dolomite	Total costs
	kg	kg	kg	kg	EUR
1	183	115	94	960	211.4
2	230	163	192	1,132	268.1
3	234	163	227	1,114	270.6
4	255	195	278	1,178	298.2
5	302	227	375	1,341	349.7
6	306	243	410	1,332	357.4
7	323	259	465	1,395	378.9
8+	370	307	563	1,568	435.6

For the sago O50 scenario, only labor for better management is needed. Annual labor requirement for sago cultivation in the O50 scenario differs by two labor days per ha compared to the O90 scenario. This difference is mainly due to the additional fertilizing labor needed in the O90 scenario, which was approximated from the oil palm plantation fertilizing labor work in [8]. The labor costs for the new sago O50 and O90 scenarios are shown in Table S5.

Table S5. Annual labor costs per ha for new sago cultivation in O50 and O90 scenarios.

YAP	Without fertilizer (O50)			With fertilizers (O90)		
	Person	Wage	Total	Person	Wage	Total
	day	EUR/day	EUR	day	EUR/day	EUR
1	55	7.5	413.9	57	7.5	429.0
2	55	7.5	413.9	57	7.5	429.0
3	55	7.5	413.9	57	7.5	429.0
4	16	7.5	120.4	18	7.5	135.5

5	16	7.5	120.4	18	7.5	135.5
6	16	7.5	120.4	18	7.5	135.5
7	16	7.5	120.4	18	7.5	135.5
8+	16	7.5	120.4	18	7.5	135.5

In the transition towards optimum yield for the current mature sago plantations (154 clusters/ha), 55% of the fertilizer and labor input costs are allocated to the existing mature plants, and the remaining 45% to the newly planted clusters (124 clusters). Both are based on the annual input cost structure in the new O50 and O90 scenarios (Table S5). The corresponding annual transition costs per hectare are presented in Table S6.

Table S6. Annual transition costs per ha for the mature sago O50 and O90 scenarios.

YAP	O50	O90
	EUR	EUR
1	249.6	601.6
2	249.6	626.5
3	249.6	627.6
4	120.4	510.6
5	120.4	533.3
6	120.4	536.7
7	120.4	546.1
8+	120.4	571.1

The annual fertilizer inputs for the new oil palm O90 scenario are presented in Table S7, where the market prices for fertilizers were as follows: triple superphosphate (TSP) at 0.85 EUR/kg, copper sulfate ($CuSO_4$) at 3.03 EUR/kg, zinc sulfate ($ZnSO_4$) at 1.46 EUR/kg, and borate at 2.28 EUR/kg. Table S8 shows the annual labor costs of the oil palm O90 scenario.

Table S7. Annual fertilizer costs per ha for the oil palm O90 scenario.

YAP	Urea	TSP	Dolomite	MOP	Rock phosphate	CuSO4	ZnSO4	Borate	Total
	kg	kg	kg	kg	kg	kg	kg	kg	EUR
1 - 2	133	217	0	0	0	0	0	0	247.8
3+	263	0	792	525	105	16	11	16	356.0

Table S8. Annual labor costs for the oil palm O90 scenario.

YAP	Person	Wage	Total
	day	EUR/day	EUR
1 - 2	36	7.85	282.5
3+	22	7.85	172.6

Section D. Input data, yields, and economic indicators

Table S9. Average annual inputs and yields in this study.

Input or output	Unit	Cassava	Corn	Sago	Oil palm
Yield	Per ha	18,528 kg	9,684 kg	36 trunks	14,900 kg
Seed or seedlings	Per ha	-	30 kg	154 seedlings	121 seedlings
Fertilizers					
Compost	kg/ha	-	-	-	1.7
$CuSO_4$	kg/ha	-	-	-	2.6
Dolomite	kg/ha	-	-	-	251
KCL	kg/ha	-	-	-	68.5
Manure	kg/ha	3,740	7,116	-	-
NPK	kg/ha	173	626	-	186
TSP	kg/ha	46	-	-	-
Urea	kg/ha	323	500	-	115
Pesticides					
Atrazine + Mesotrione	L/ha	-	1.8	-	-
Azoxystrobin + Difenoconazole	L/ha	-	0.2	-	-
Carbosulfan	kg/ha	-	-	-	0.1
Clothianidin	L/ha	-	0.05	-	-
Diuron	kg/ha	-	1.0	-	-
Glyphosate	L/ha	3.7	-	-	-
Paraquat	L/ha	0.6	1.2		10
Profenofos	L/ha	-	0.7	-	-

Table S10. Subsidized vs non-subsidized fertilizer costs at the farm gate (EUR/kg).

	Cassava	Corn	Sago	Oil palm
Subsidized Urea	0.28	0.15	-	-
Non-subsidized Urea	0.64	0.64	-	0.48
Subsidized NPK	0.28	0.16	-	-
Non-subsidized NPK	0.77	0.77	-	0.44

Note: The official prices for subsidized Urea and NPK fertilizers, as set by the Minister of Agriculture Regulation No. 10/2022, were 0.137 EUR/kg and 0.140 EUR/kg, respectively. However, farm-gate prices were higher due to additional supply chain costs. Cassava farmers, who were not eligible for subsidies, often obtained subsidized fertilizers through informal channels, which made them more expensive. Oil palm farmers used non-subsidized fertilizers and typically opted for lower-cost brands.

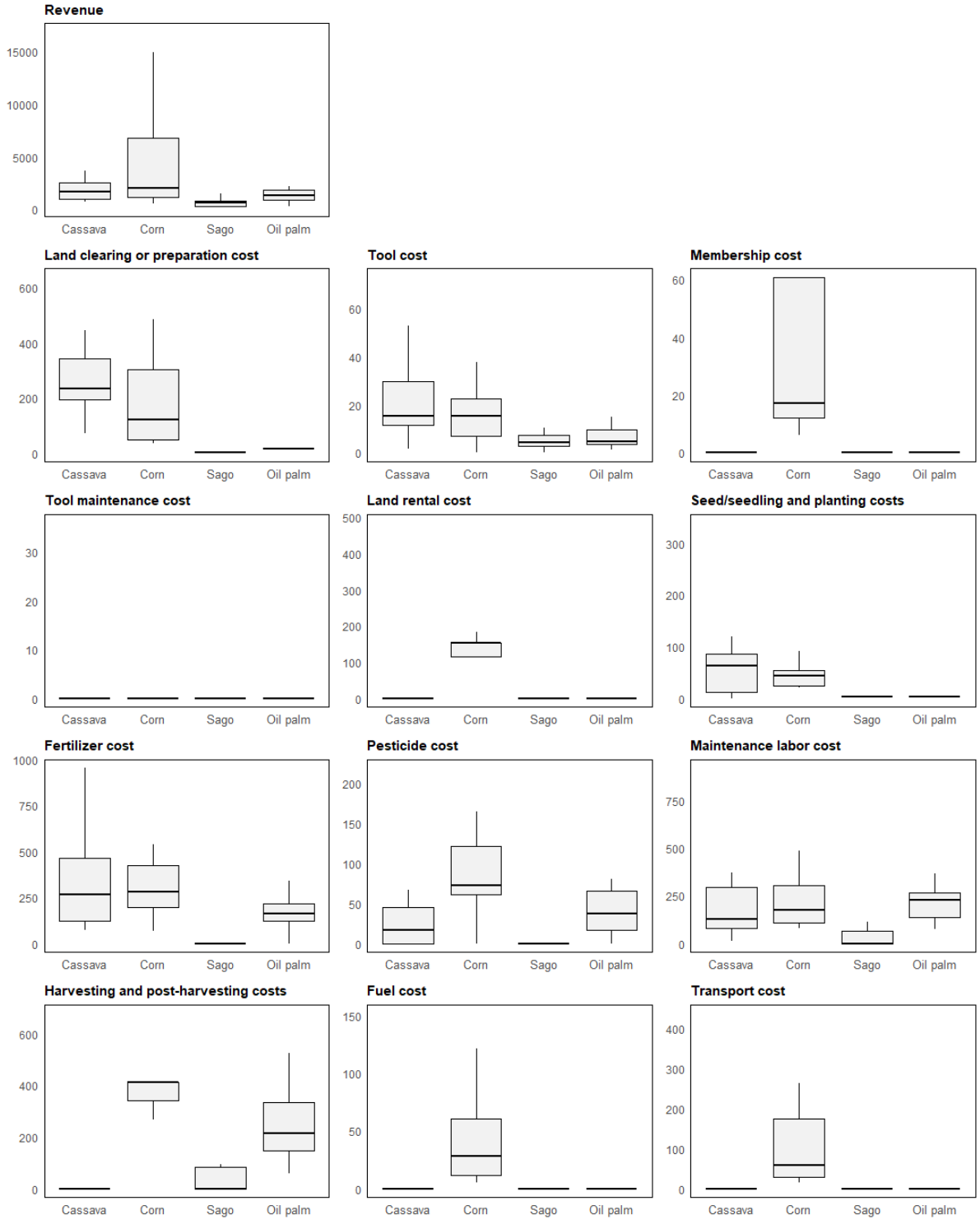

Figure S1. Boxplots of the annual revenue and costs for all crops (EUR/ha).

Section E. Annual net revenues

Table S11. Baseline annual cash flows for all crops (EUR/ha, before discounting).

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Cassava	885	885	885	885	885	885	885	885	885	885	885	885	885
Corn	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553
Sago	-36	-36	-36	-36	-36	-36	-36	732	732	732	732	732	732
Oil palm	-493	-493	-105	188	322	459	703	853	938	938	938	938	938

Year	14	15	16	17	18	19	20	21	22	23	24	25
Cassava	885	885	885	885	885	885	885	885	885	885	885	885
Corn	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553	1,553
Sago	732	732	732	732	732	732	732	732	732	732	732	732
Oil palm	887	829	789	728	676	628	577	532	447	398	350	299

Table S12. Baseline annual cash flows for all crops (EUR/ha, after discounting).

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Cassava	769	669	582	506	440	382	333	289	251	219	190	165	144
Corn	1,351	1,175	1,021	888	772	672	584	508	442	384	334	290	252
Sago	-32	-28	-24	-21	-18	-16	-14	239	208	181	157	137	119
Oil palm	-429	-373	-69	107	160	198	264	279	267	232	202	175	152

Year	14	15	16	17	18	19	20	21	22	23	24	25
Cassava	125	109	95	82	71	62	54	47	41	36	31	27
Corn	220	191	166	144	126	109	95	83	72	62	54	47
Sago	103	90	78	68	59	51	45	39	34	29	26	22
Oil palm	125	102	84	68	55	44	35	28	21	16	12	9

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