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Evaluating the Economic Feasibility of Plant Factory Scenarios That Produce Biomass for Biorefining Processes

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Supplementary Materials

The information provided below is the supplementary information and intermediate data associated with the economic model and economic feasibility analyses which were discussed in the corresponding paper.

1. Literature review of key themes and terms for the plant factory system boundary

The expanded terms mentioned in this section were used to develop the conceptual plant factory system boundary and correlate the identified key terms to economic indexes for plant factory systems.

Table S1. Plant factory design and operational considerations

Theme	Term	Considerations	References
Design	Structural design	Determining the degree of environmental insulation required	[1–8]
		Determination of plant factory production capacity and ease of capacity increase	[5,9–13]
		Construction material use and environmental impact of intended development	[2,6,14–20]
	Technology	Energy generation infrastructure	[21–31]
		Water capture- and utilisation infrastructure	[1,19,32–36]
		Determination of automated environmental control system complexity	[5–7,37–40]
		Correlation between design complexity and plant factory biomass performance	[1,3,5,6,14,31,41–43]
Operations	Resource inputs	Selection of physical labour harvesting or automation	[5,6,10,13,39,42,44,45]
		Selection of grid energy or renewable energy sources	[5,19,27,31,33,46–50]
		Water resource management	[1,35,36,39,51,52]
		Determination of CO_2 enrichment levels	[2,7,10,53–58]
		Selection of appropriate land	[10,15,17,18,36,54,59–61]
		Selection of fertiliser, pesticide and seed suppliers	[5,10,36,53,61–65]
	Resource outputs	Determining emissions and waste quantities	[2,10,66–69]
		Plant factory product storage requirements	[8,10,67,70–72]

Table S2. Supply chain considerations as part of a plant factory system boundary

Theme	Term	Considerations	References
Supply chain	Network configuration	Plant factory site numbers and locations	[9,73–77]
		Plant factory supplier locations	[78–82]
		Plant factory product market locations	[8,9,72,78,81–84]
	External industries	Identification of external waste streams for valorisation	[28,69,71,84–87]
		Determining the degree of vertical integration of feedstock production and processing within the plant factory system boundary	[88–92]
	Uncertainty	Selection of biomass which can service multiple markets	[77,83,93–95]
		Determination of supply chain performance	[73,96–99]
		Transportation logistics for produced biomass	[9,82,84,96,100,101]
		Regional policies concerning biomass production and bioprocessing industries	[60,73,80,84,94–96,102]

Table S3. Biorefining market considerations for plant factory projects

Theme	Term	Considerations	References
Biorefining markets	Biomass selection	Determination of biomass demand	[9,82–84,96,99]
		Identification of alternative biomass suppliers	[9,83,96,103,104]
		Required chemical and physical properties	[9,16,56,73,81,83,105]
	Downstream markets	Selection of end-products and appropriate co-derived intermediate products from produced biomass	[77,81,83,97,103,106,107]
		Calculation of intermediate and end-product prices	[73,81,82,84,103,108,109]

2. Economic model equations

This section provides the intermediate plant factory economic model equations used to calculate CAPEX and OPEX costs for each of the investigated plant factory scenarios.

2.1 Capital Expenditure (CAPEX) calculations

The construction cost in Equation (S1) was divided into structure cost and real estate cost. The real estate cost was omitted from further calculations as its value was too heavily dependent on the selection of a specific location for the plant factory scenarios.

$$\text{Construction cost} = \text{Structure cost} + \text{Real estate} \tag{S1}$$

The structure cost was calculated using the defined plant factory floorspace breakdown in Table 3 and the report by Turner & Townsend [110] which specified the cost of construction in South Africa. The cost calculations are shown in Table S6. The equipment cost in Equation (S2) was divided into equipment components which were costed individually for each of the plant factory scenarios.

$$\text{Equipment cost} = \text{Grow system module} + \text{Lift and transport} + \text{Fertigation system} + \text{Monitor and control system} + \text{Heating, ventilation and air conditioning (HVAC) system} \quad \text{(S2)}$$

The individual costing of the equipment components is shown in Table S7 to Table S9. The depreciation of the structure and equipment was also included in Equation (S3) as it is often ignored when evaluating the economic feasibility of plant factories [111].

$$\text{Depreciation per year} = (\text{Structure cost})/(\text{Structure lifespan}) + (\text{Equipment cost})/(\text{Equipment lifespan}) \quad \text{(S3)}$$

The depreciation cost was calculated individually for each of the equipment components as they had different lifespans.

2.2 Operating Expenditure (OPEX) calculations

Equation (S4) shows that the variable cost, also cost of goods sold (COGS), included direct labour costs, total electricity costs, water, fertiliser, grow media, seeds and additional CO_2.

$$\text{COGS} = \text{Direct labour} + \text{Electricity} + \text{Water} + \text{Fertiliser} + \text{Grow media} + \text{Seeds} + CO_2 \quad \text{(S4)}$$

The values of the COGS components used in the simulations are tabulated in Table S10 to Table S16. The direct labour cost, Equation (S5), was a function of salary rates, total labourers and working hours per year for each labourer.

$$\text{Direct labour cost} = \text{Salary rates} \times \text{Total labourers} \times \text{labour hours per year for each labourer} \quad \text{(S5)}$$

The wage rates for direct labour positions and the labourer to cultivation area estimates are also shown in Table S10. The electricity required to power the light emitting diode (LED) lighting system was calculated with Equation (S6) and took into account the variations in photoperiods between crops, the required number of LED lights to achieve the desired canopy light intensity and the variations in electricity tariffs.

$$\text{Annual electricity cost for LED lighting} = \text{Number of LED lights} \times \text{Watts per light} \times \text{Photoperiod} \times \text{Operational days per year} \times \text{Electricity tariff} \quad \text{(S6)}$$

Table S11 summarises the technical specifications of the LED lighting system used in the model and summarises the differences of the LED lighting system for each of the crops being investigated. The energy tariff was estimated using the wholesale electricity pricing system (WEPS) as published by the South African electricity public utility, Eskom [112]. The electricity tariff structure in Equation (S7) consisted of an active energy charge, ancillary service charge, electrification and rural network subsidy charge and affordability subsidy charge.

$$\text{Electricity tariff} = \text{Active energy charge} + \text{Ancillary service charge} + \text{Electrification and rural network subsidy charge} + \text{Affordability subsidy charge} \quad \text{(S7)}$$

The WEPS pricing structure is tabulated in Table S12 with active energy charge rates for off-peak and standard times. Equation (S8) was used to calculate the total cooling load required for the plant factory grow area and considered heat removal from the ventilation air, LED lighting systems, plant evapotranspiration and heat gained from the environment.

$$\text{Heat removed} = \text{Heat removed from ventilation air} + \text{Heat from LED lights} + \text{Heat from plant evapotranspiration} + \text{Heat gained from the environment} \quad (S8)$$

The components of Equation (S8) were calculated using Equation (S9) to Equation (S12) and are shown in Table S13:

$$\text{Heat removed from ventilation air} = \text{Heat capacity of air} \times \text{mass flow rate of air} \times (\text{Average ambient air temperature} - \text{Average indoor air temperature}) \quad (S9)$$

$$\text{Heat from LED lights} = \text{Percentage heat generation from LEDs} \times \text{Power per LED bar} \times \text{Light bars required for growing area} \quad (S10)$$

$$\text{Heat from plant evapotranspiration} = (\text{Annual water requirement} \times \text{Water density} \times \text{Heat of vaporisation}) / (\text{Total seconds per year of heat removal}) \quad (S11)$$

$$\text{Heat gained from the environment} = \text{Heat transfer coefficient} \times \text{Surface area of growing room walls} \times (\text{Average ambient air temperature} - \text{Average indoor air temperature}) \quad (S12)$$

The annual electricity demand was calculated by using Equation (S13) and by considering the total operational hours per year of the plant factory. The electricity demand of LED heat removal was based on daily photoperiods and the heat removal associated with ventilation air, evapotranspiration and the environment were calculated on a 24 hour per day basis.

$$\text{Electricity required} = (\text{Heat removed}) / (\text{Coefficient of performance (COP)}) \quad (S13)$$

The cost of water demand, Equation (S14), can be related to evapotranspiration rates of crops. This economic model used the Blaney-Criddle equation, Equation (S15), to estimate the water demand of the plant factory scenarios [113].

$$\text{Water cost} = \text{Evapotranspiration rate} \times \text{Total growing area} \times \text{Water tariff} \quad (S14)$$

The results obtainable from the Blaney-Criddle equation were assumed to be sufficiently accurate for the complexity of this model. The water tariff and evapotranspiration values are tabulated in Table S14, along with the fertiliser concentration and price data.

$$\text{Evapotranspiration rate} = \text{Crop factor} \times \text{Mean daily percentage of annual daytime hours} \times (0.46 \times \text{Mean daily temperature} + 8) \quad (S15)$$

The annual fertiliser cost, Equation (S16), was based on the annual water requirement, fertiliser concentration and fertiliser selling price.

$$\text{Fertiliser cost} = \text{Water required} \times \text{Fertiliser concentration} \times \text{Fertiliser price} \quad \text{(S16)}$$

The grow media cost, Equation (S17), was calculated by considering the total amount of plants being cultivated each year and the amount of times the grow media could be reused before disposal. Rockwool was selected as the grow media and information regarding the substrate is tabulated in Table S15.

$$\text{Grow media cost} = (\text{Plants grown per year})/(\text{Grow media uses}) \times \text{Grow media price} \quad \text{(S17)}$$

Similarly, the annual seed requirement, Equation (S18), was based on the projected amounts of plants being cultivated each year and the germination rate.

$$\text{Seed cost} = \text{Plants grown per year} \times 100/(\text{Germination rate}) \times \text{Seed price} \quad \text{(S18)}$$

Lastly, the supplemental CO_2 flow rate was calculated in Equation (S19) by elevating the CO_2 concentration in the ventilation air to the desired level, prior to entry into the grow room, and by compensating for the CO_2 uptake rate of the cultivated plants in the plant factory to ensure the desired level of CO_2 in the cultivation space.

$$CO_2 \text{ flow rate} = \text{Elevated } CO_2 \text{ levels in the ventilation air} + CO_2 \text{ uptake of cultivated plants} \quad \text{(S19)}$$

The CO_2 uptake rate in the plant factory space was assumed [11,71] and the CO_2 that was required to supplement the ventilation air was calculated using Equation (S20).

$$CO_2 \text{ required for ventilation air} = \text{Air flow rate} \times (\text{Desired } CO_2 \text{ levels in parts per million} - \text{Ambient } CO_2 \text{ levels in parts per million})/(10^{\wedge 6}) \quad \text{(S20)}$$

The CO_2 uptake rates, intermediate calculations and supplementing data are shown in Table S16 for each of the investigated crops.

3. Economic model assumptions and general information

This section includes the main assumptions and general information which was used to populate the plant factory economic model.

Table S4. Economic model assumptions

nr.	Assumption	Motivation
	General	
1	Constant plant factory footprint size throughout scenarios	Constrains the scenarios and makes direct comparisons easier
2	Real estate cost omitted	Location-specific and constant throughout the scenarios
3	Plant factory environmental conditions and associated crop yields based on literature data	Linking the biomass yields and cultivating conditions in the model provides a measure of certainty to the revenue calculations
4	Currency exchange rates taken as of April 2022 South African Rand/Dollar (US) = 14.85 South African Rand /Dollar (Canadian) = 11.88 South African Rand /Euro = 16.16	Provides consistency throughout the study
5	Loan repayments and tax not considered	Ease of calculations
6	Favourable cultivation area to labourer ratio assumed	High-tech plant factory facility can be designed to require minimal physical input
7	Plant factory assumed operational 335 days per year	-
8	Single-value prices represented with a price range of 20% uncertainty.	-
	CAPEX	
9	Plant factory structure cost approximated using published construction costs of similar structures	-
10	Plant factory racks have adjustable tray heights and do not impact CAPEX calculations	-
11	Plant factory footprint breakdown remains constant	Footprint components are based on literature and not varied for simplicity
12	Lift and transport car (R100,000) included for each scenario	Helps with direct labour activities and its inclusion motivates the favourable labourer to cultivation area ratios which are used in the model
13	Plant factory grow module price includes trays, racks, piping, pumps and the LED lighting system	Cost estimates of the individual components were difficult to obtain and instead a cost per cultivation area price was calculated using price estimates of a plant factory module with the specified components included
14	The monitor and control system consisted of four (4-in-1) sensors per level per vertical farming rack	Assumed to be adequate sensor equipment for a 600 m^2 footprint growing area
15	The monitor and control system consisted of four temperature, humidity and CO_2 controllers and one lighting controller per level per rack	Assumed to be adequate environmental control equipment for a 600 m^2 footprint growing area
16	The cost of the HVAC system was estimated as 4% of the total plant factory equipment cost	-

17	The high-wire cultivation module cost was approximated as a one level hydroponic tray system	-
18	High-wire row takes up similar cultivation space to a vertical farming rack	Conservative estimate for ease of calculations
19	One high-wire row has a sensor density equal to two levels of a vertical farming rack	-
20	The nutrient delivery system consists of one commercially available fertigation system and four batch tanks as liquid fertiliser reservoirs	-
	OPEX	
21	Insurance and rent excluded	Ease of calculations
22	Peak energy load times are avoided to lower electricity tariff	-
23	Elevated CO_2 levels only provided during photoperiod	-
24	The high-wire module CO_2 uptake and water requirements are based on the total vertical cultivation area	-
25	Grow slabs can hold three vines each in the high-wire module	-
26	Lighting and HVAC energy consumption approximated as 98% of total energy demand	-
27	Ventilation rate remains constant at nine times per day	-
28	Moneymaker and dwarfed tomato seed prices assumed same as micro-tom tomato seeds	Lack of available data
29	Grow media reusable four times before disposal is required	-
30	Direct labour hours are twenty per week	-
31	Heat generated from LED lighting system is equal to 50% of the energy demand of the system	-
32	Heating and cooling load of the HVAC system is only based on the growing area space	-
33	Growing area is highly insulated with a 0.3 W/(m^2.K) heat transfer coefficient	-
34	Growing area walls have a 400 m^2 surface area	-
35	HVAC system has a coefficient of performance (COP) of 3	-
	Crop data	
36	Fresh weight biomass consists of 75 wt% moisture	-
37	Miracle berry value related to miraculin content	-
38	Cultivation periods used in the model are considered as days after transplanting	Nursery cultivation is excluded as it does not share the same growing space as the transplanted biomass
39	Conventional tobacco cultivation in a hydroponic system is approximated using open-field tobacco yields, plant dimensions, planting densities and cultivation periods of the Solaris cultivar	Ease of calculation
40	Artemisinin accumulation does not influence biofuel production using the same tobacco feedstock	-
41	Artemisinin accumulation does not inhibit growth of the host plant	-
42	Transgenic tobacco and dwarf variants are both cultivated in five level vertical growing racks	For ease of calculations, the difference in size is reflected in planting density and not additional cultivation layers
43	Transgenic tobacco and dwarf variant planting densities based on lettuce densities	Similar plant dimensions

44	Cannabis evapotranspiration rates assumed	-
45	The CO_2 uptake rate in a plant factory is kept at 4-6 g/m^2 grow area/h photoperiod	-

Table S5. General information used in the plant factory model

	Unit	Value	Reference
Plant factory information			
Grow room air replenish rate	times/day	9	[11,114]
Grow room volume	m^3	2400	-
Air flow rate	m^3/h	900	-
Grow room surface area	m^2	400	-
Grow room walls heat transfer coefficient	W/(m^2.K)	0.3	Assumed
Meteorological information			
Average ambient day temperature	°C	25	[115]
Average ambient night temperature	°C	15	[115]
Ambient CO_2 by volume	ppm	400	Assumed
Heat transfer properties			
Heat of vaporisation for water at 25°C	kJ/kg	2442	-
Density of water at 25°C	kg/m^3	997	-
Heat capacity of air at 25°C	kJ/(kg.K)	1.005	-
Density of air at 25°C	kg/m^3	1.184	-
Density of CO_2 at 25°C	kg/m^3	1.81	
Coefficient of performance	-	3	Assumed

4. Economic model CAPEX intermediate data

This section provides all the supplementary information and calculations associated with the plant factory CAPEX calculations of the developed economic model.

Table S6. The plant factory footprint (1000 m^2) components equated to typical structure construction costs in South Africa

Plant factory component	Space breakdown (%)	Turner & Townsend equivalent space	Construction cost (R/m^2)	Reference
Germination and nursery	15	High-tech laboratory/factory	9,100	[110]
Growth phase bottom layer	60	Warehouse/factory - basic	5,100	
Harvest, packaging and storage	15	Warehouse distribution centre	5,500	
Walkways, offices and ancillary spaces	10	Office - Business park	13,000	
Total	100	-	-	

The grow system infrastructure cost was calculated from price estimates of vertical farming plant factory grow racks with different levels of grow trays [116]. The price estimates are shown in Table S7 and were used to calculate an average cost per vertical farming level per rack. The grow area per grow rack level remained constant at 1.6 m x 20 m.

Table S7. Plant factory cost estimates and calculated cost per grow level

Plant factory grow rack	Grow level	Price estimate (R)	Cost per grow level (R/level)	Included	Excluded	Reference
3816 Plant system	3	581,756	193,919	• Grow racks • Grow trays • LED lighting • Hydroponic piping • Water pump	• Fertigation system • HVAC system • Monitor and control system • Sensors • Shipping and installation	[116]
5088 Plant system	4	775,675	193,919			
6360 Plant system	5	969,594	193,919			
10,176 Plant system	8	1,717,669	214,709			
12,270 Plant system	10	2,124,625	212,463			
Average cost			**201,785**			

Table S8. Fertigation system cost calculations

Fertigation system component	Price estimate (R)	Reference
Nutrient control and pumping system	257,440	[117]
Liquid nutrient reservoir tanks	71,280	[118]
Total	**328,720**	

Table S9. Monitor and control cost calculations

		Scenarios with five levels	High-wire (TF)	Scenario (CC) with three levels	
Component	**Cost per component (R)**		**Quantity**		**Reference**
Hydro-X-Pro	51,920	7	3	5	[119]
MBS-PRO 4-in-1 sensor	5,910	340	136	204	
Temperature controller	1,604	4	4	4	
Humidity controller	1,478	4	4	4	
CO2 controller	995	4	4	4	
Lighting controller	1,277	85	17	51	
Total cost (R)		**2,497,801**	**997,577**	**1,546,739**	

5. Economic model OPEX intermediate data

This section provides all the supplementary information and calculations associated with the plant factory OPEX calculations of the developed economic model.

Table S10. Salary and position breakdowns

Position	Quantity	Minimum (R/h)	Average (R/h)	Maximum (R/h)	Hours per week (h/week)	Cultivation area per labourer (m^2/labourer)	Reference
Manager	1	182	249	308	40	-	[120]
Arborist	1	79	103	124	40	-	[121]
Cleaner	1	55	69	82	40	-	[122]
Admin	1	116	161	197	40	-	[123]
Marketing	1	165	226	281	40	-	[124]
Labourer (vertical farm)	3 2[a]	18	49	56	20	1250	[11,125,126]
Labourers (high-wire)	2	18	49	56	20	1700	[11,125,126]

[a]Two labourers for scenario CC due to smaller growing area of 1632 m^2.

Table S11. LED light system specifications and electricity use

	Unit	Value	Reference
LED lighting system specifications			
LED bar length	m	1.1	[127]
LED bar width	m	0.045	
Power per LED bar	W	63	
Efficiency	µmol/J	2.55	
Photosynthetic Photon Flux (PPF)	µmol/s	161	
Photosynthetic Photon Flux Density (PPFD) 30cm from light source for 10 bars	µmol/m^2/s	900	
Photosynthetic Photon Flux Density (PPFD) 30cm from single bar	µmol/m^2/s	90	Assumed

LED energy consumption

Scenario specifications	Unit	Lettuce	Tomato (dwarf)	Tomato (high-wire)	Tobacco	Cannabis
PPFD required	µmol/m^2/s	200	400	600	275	500
Light bars per grow area	bar/m^2	3	5	7	4	6
Total grow area	m^2	2720	2720	1020	2720	1632
Light bars required for grow area	-	8160	13600	7140	10880	9792
Photoperiod	h	16	12	12	13	16
Annual operating days	days	335	335	335	335	335
Annual energy requirement	kWh	2,755,469	3,444,336	1,808,276	2,985,091	3,306,563

Table S12. Electricity pricing structure

	Unit	Minimum (off-peak) pricing	Average	Maximum (standard) pricing
Ancillary service charge	c/kWh	0.61	-	0.61
Electrification and rural network subsidy charge	c/kWh	13.37	-	13.37
Affordability subsidy charge	c/kWh	6.54	-	6.54
Active energy charge	c/kWh	74.99	-	123.72
Total		96	120	144

Table S13. HVAC calculations for plant factory scenarios

		Scenarios based on crop				
	Unit	Lettuce	Tomato (dwarf)	Tomato (high-wire)	Tobacco	Cannabis
Heat generated from LED lights	%	50	50	50	50	50
Heat removed from LED lights	kW	257	428	225	343	308
Heat removed from evapotranspiration	kW	164 (min) 219 (average) 365 (maximum)	189 (min) 315 (average) 483 (maximum)	71 (min) 118 (average) 118 (maximum)	166 (min) 356 (average) 522 (maximum)	206 (min) 253 (average) 301 (maximum)
Heat gained from the environment	kW	0.36	-0.30	-0.30	-0.90	-0.72
Heat removed from ventilation air	kW	0.89	-0.74	-0.74	-2.23	-1.78
Total heat removal from grow area	kW	423 (min) 478 (average) 624 (maximum)	616 (min) 742 (average) 910 (maximum)	295 (min) 342 (average) 405 (maximum)	506 (min) 696 (average) 862 (maximum)	511 (min) 559 (average) 607 (maximum)
COP	-	3	3	3	3	3
Peak electricity required	kW	141 (min) 159 (average) 208 (maximum)	205 (min) 247 (average) 303 (maximum)	98 (min) 114 (average) 135 (maximum)	169 (min) 232 (average) 287 (maximum)	170 (min) 186 (average) 202 (maximum)
Annual electricity demand (minimum)	kWh	**903,357**	**1,077,587**	**488,453**	**934,345**	**1,095,129**
Annual electricity demand (average)	kWh	**1,050,274**	**1,415,141**	**615,036**	**1,443,179**	**1,223,638**
Annual electricity demand (maximum)	kWh	**1,442,054**	**1,865,213**	**783,813**	**1,888,410**	**1,352,148**

Table S14. Water consumption and fertiliser data for plant factory scenarios

		Scenarios based on crop					Reference
	Unit	Lettuce	Tomato (dwarf)	Tomato (high-wire)	Tobacco	Cannabis	
Mean daily percentage of annual daytime hours	-	0.30	0.30	0.30	0.30	0.30	-
Mean daily temperature	°C	17	23	23	28	26	-
Crop factor (minimum)	-	0.45	0.45	0.45	0.35	0.75[a]	-
Crop factor (average)	-	0.6	0.75	0.75	0.75	0.93[a]	-
Crop factor (maximum)	-	1.00	1.15	1.15	1.10	1.10[a]	-
Evapotranspiration rate (minimum)	m/day	0.0021	0.0025	0.0025	0.0022	0.0045	-
Evapotranspiration rate (average)	m/day	0.0029	0.0041	0.0041	0.0046	0.0055	-
Evapotranspiration rate (maximum)	m/day	0.0048	0.0063	0.0063	0.0068	0.0066	-
Evapotranspiration rate (minimum)[b]	**m^3/year**	**1955**	**2246**	**842**	**1975**	**2443**	**-**
Evapotranspiration rate (average)[b]	**m^3/year**	**2607**	**3743**	**1404**	**4232**	**3013**	**-**
Evapotranspiration rate (maximum)[b]	**m^3/year**	**4345**	**5740**	**2152**	**6207**	**3583**	**-**
Water tariff	R/m^3	28.39	28.39	28.39	28.39	28.39	[128]
Fertiliser cost	R/kg	69.30	69.30	69.30	69.30	69.30	[129]
Fertiliser concentration	kg/m^3	1.11-1.85	1.11-1.85	1.11-1.85	1.11-1.85	1.11-1.85	[129]

[a]Cannabis crop factor values assumed.
[b]Evapotranspiration by per year was calculated using the evapotranspiration rate (m/day) and the grow areas of the plant factory scenarios.

Table S15. Grow media and seed demand for plant factory scenarios

	Unit	Value	Reference
Grow media			
Rockwool slab price	R/slab	63 - 94	[130]
Rockwool cube price	R/cube	9 - 13	[131]
Rockwool plug price	R/plug	2 - 3	[132]
Rockwool density	kg/m^3	19.8	[132]
Brewers' spent grain price	R/kg	3.70 – 4.50	[133]
Brewers' spent grain density	kg/m^3	450	[134]
Crop seeds			
Tomato price	R/seed	0.24	[135]
Lettuce price	R/seed	0.07	[136]
Tobacco price	R/seed	1.20	[137]
Cannabis price	R/seed	74.25 – 103.95	[138]

Table S16. CO_2 supplement for plant factory scenarios

		Scenarios based on crop				
	Unit	Lettuce	Tomato (dwarf)	Tomato (high-wire)	Tobacco	Cannabis
CO_2 uptake rate in grow area	g/m^2 grow area/h photoperiod	4-6				
CO_2 cost	R/kg	11				
Desired CO_2 level by volume	ppm	1000	1000	1000	750	950
CO_2 flow rate for desired level	m^3/h	0.54	0.54	0.54	0.32	0.495
Density of CO_2 at 25°C	kg/m^3	1.81				
CO_2 flow rate for desired levels	kg/h photoperiod	0.98	0.98	0.98	0.57	0.90
CO_2 uptake rate in grow area	kg/h photoperiod	10.88 – 16.32	10.88 – 16.32	4.08 – 6.12	10.88 – 16.32	6.53 – 9.80
Total CO_2 flow rate	kg/h photoperiod	11.86 – 17.30	11.86 – 17.30	5.06 – 7.10	11.86 – 17.30	7.42 – 10.69
Total CO_2 flow rate cost	**R/h photoperiod**	**131 - 192**	**131 - 192**	**56 - 79**	**131 - 192**	**82 - 119**

6. Plant factory economic analysis intermediate results

This section provides intermediate and supplementary data for the economic feasibility analysis.

Table S17. Plant factory dimension descriptions for each scenario

		Scenarios							
	Unit	TF	TM	LF/LM/LRI	TC	TPHB	TT	TTD	CC
Structure									
Total footprint	m^2	1000	1000	1000	1000	1000	1000	1000	1000
Grow chamber floor area	m^2	600	600	600	600	600	600	600	600
Structure height	m	4	4	4	4	4	4	4	4
Grow chamber									
Grow racks	-	17 (rows)	17	17	17	17	17	17	17
Grow levels per rack	-	High-wire (3 m)	5	5	5	5	5	5	3
Grow rack length	m	20 (row)	20	20	20	20	20	20	20
Grow rack width	m	1.78 (row)	1.78	1.78	1.78	1.78	1.78	1.78	1.78
Grow area per level	m^2	-	32	32	32	32	32	32	32
Grow area per rack	m^2	-	160	160	160	160	160	160	96
Total grow area	m^2	1020	2720	2720	2720	2720	2720	2720	1632
Crop data									
Plant heights	cm	<300	20 - 40	15 - 30	<100	<100	<60	<25	<140
Plant height references	-	[139]	[140]	[141]	[142]	[143]	[144]	[144]	[145]

Table S18. Miraculin cost estimates based on miracle berry prices and sucrose equivalency

	Unit	Value	Reference
Miracle berry equivalent pricing			
Miracle berry fresh weight	g/berry	1	[146]
Miraculin content in miracle berry	µg/g	400	[146]
Miraculin content in miracle berry	µg/fruit	400	-
Miracle berry price	R/g	29.70	[147,148]
Miraculin price	R/ µg	0.074	-
Miraculin price	**R/kg**	**74,250,00 ± 20%**	-
Sucrose equivalent pricing			
Miraculin molecular weight	g/mol	24,600	[149]
Sucrose molecular weight	g/mol	342	[150]
Miraculin:Sucrose molecular ratio for equivalent sweetness	-	4×10^{-7}:0.4	[149]
Miraculin:Sucrose mass ratio for equivalent sweetness	-	1:13902	-
Sucrose (sugar) price	R/kg	20 - 28	[151,152]
Miraculin price of 1 kg based on 13,902 kg sucrose	**R/kg**	**278,049 – 389,268**	-

The sensitivity analysis of the COGS value for TF is shown in Figure S1 and shows that the COGS was most sensitive to electricity tariff changes, HVAC energy demand and fertiliser requirements. The electricity required for LED lighting was not presented as a value range and was calculated as a fixed value for each of the investigated scenarios. The impact of LED electricity requirements was reflected in the electricity tariff variable as the tariff rate applied to electricity demands for lighting, HVAC and ancillary equipment. A breakdown of the electricity demand for lighting and HVAC is shown in Table S11 to Table S13.

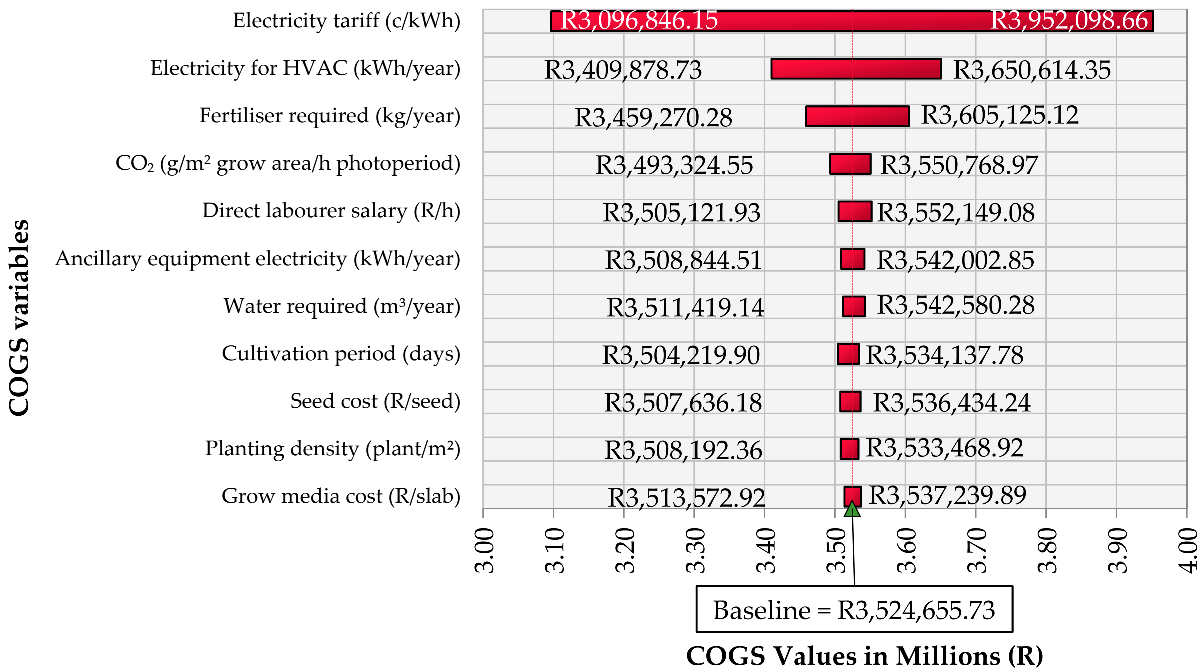

Figure S1. The sensitivity of cost of goods sold (COGS) values for the tomato–food (TF) plant factory scenario.

The elevated COGS values for TM were attributed to the larger growing area and higher planting densities. This resulted in more plants being cultivated each year and led to elevated variable costs and was reflected in Figure S2. Electricity usage was especially impacted as additional lighting was required to cover the entire growing area of the vertically stacked grow racks in TM.

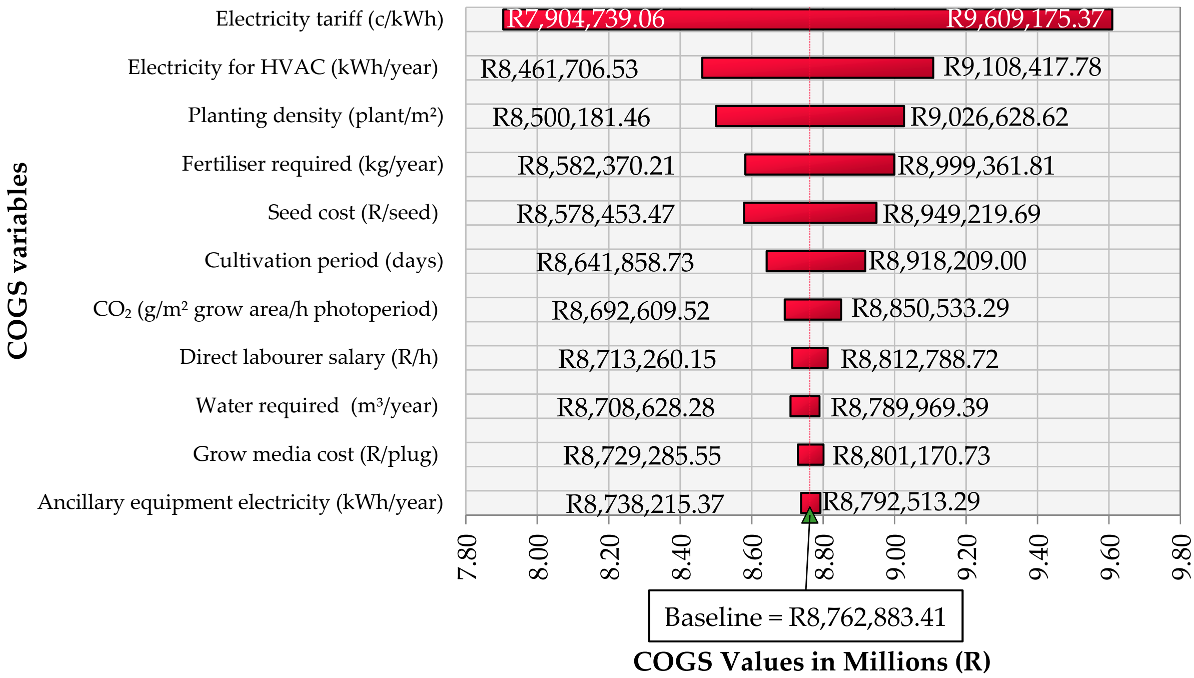

Figure S2. The sensitivity of cost of goods sold (COGS) values for the tomato–miraculin (TM) plant factory scenario.

The sensitivity analysis of COGS values for the baseline LF scenario, Figure S3, shows that electricity, fertiliser and grow media costs were among the biggest cost drivers. Based on these results, it was decided to use the LRI scenario to investigate energy cost reductions by using PV panels [23] for renewable energy generation. The integration of a plant factory with a beer brewing plant allowed for the valorisation of brewers' spent grains [10,153] into grow media and wastewater into liquid fertiliser for hydroponic cultivation [154]. The integration component of LRI only considered cost reduction by using brewers' spent grains for grow media as the cost of using anaerobically digested brewery wastewater was unknown.

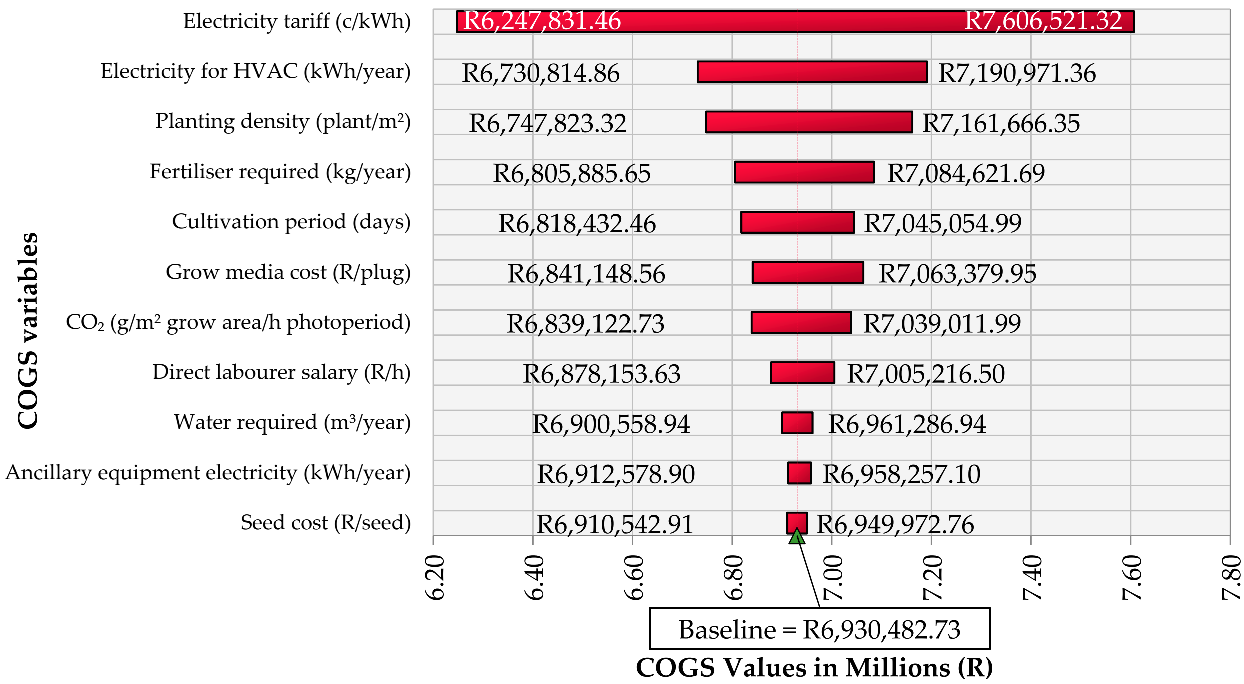

Figure S3. The sensitivity of cost of goods sold (COGS) values for the lettuce–food (LF) plant factory scenario.

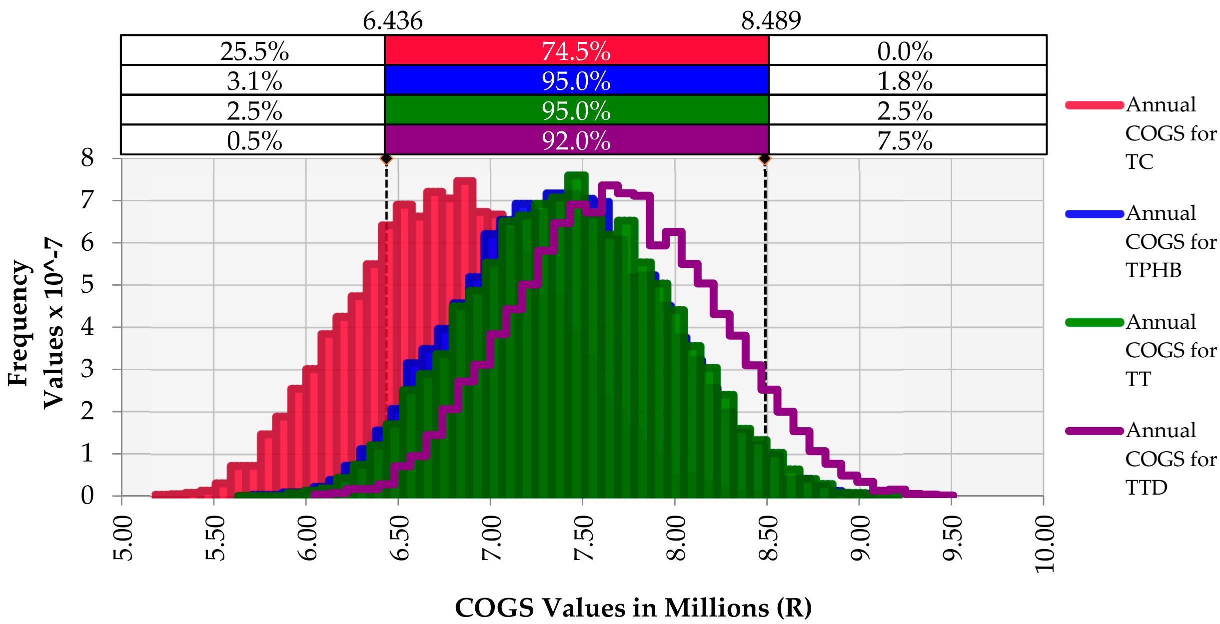

Figure S4. Probability density distributions of the cost of goods sold (COGS) for the tobacco–conventional (TC), tobacco–PHB (TPHB), tobacco–transgenic (TT) and tobacco–transgenic-dwarf (TTD) plant factory scenarios.

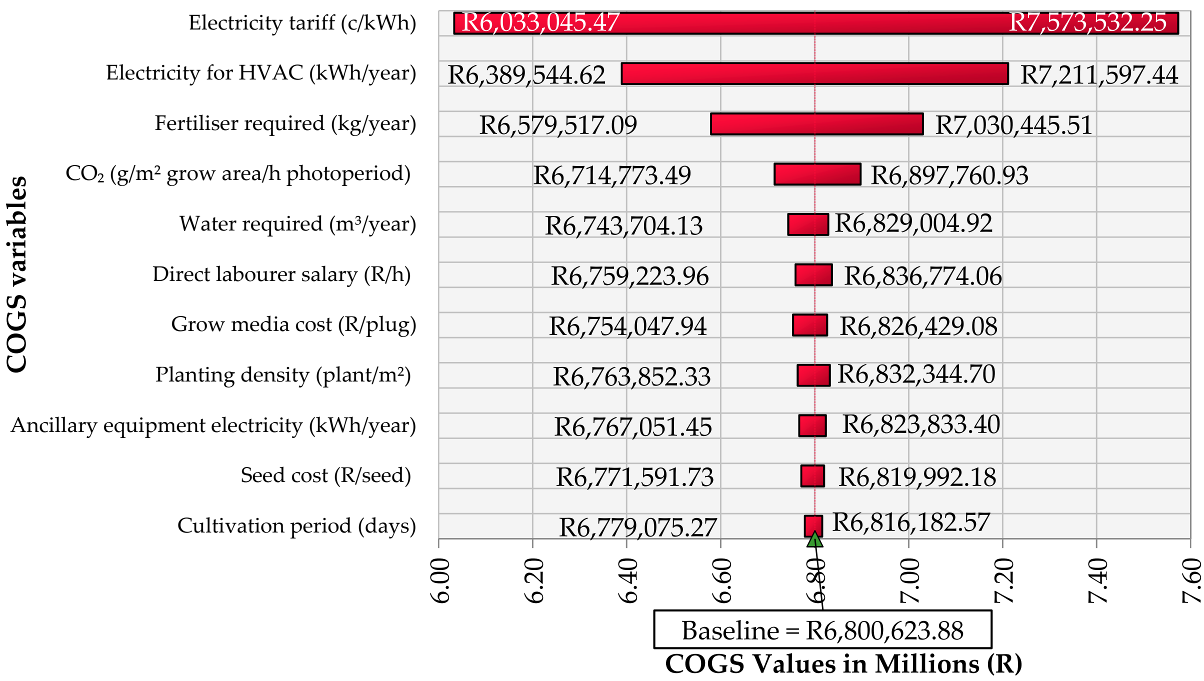

Figure S5. The sensitivity of cost of goods sold (COGS) values for the tobacco–conventional (TC) plant factory scenario.

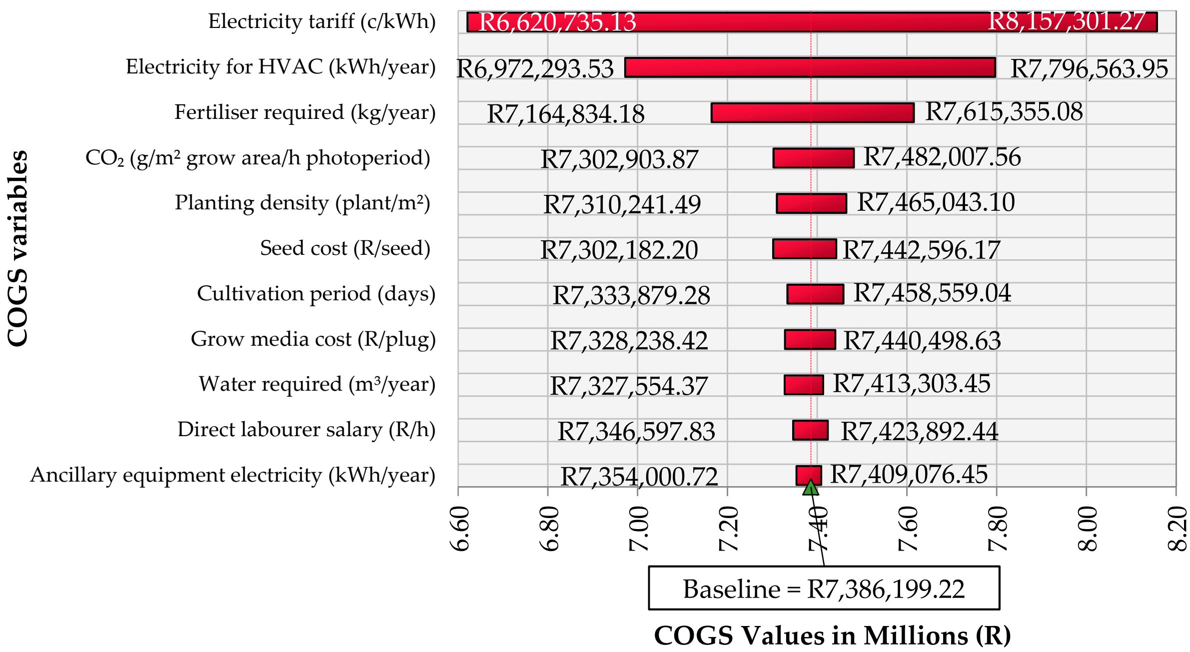

Figure S6. The sensitivity of cost of goods sold (COGS) values for the tobacco–PHB (TPHB) plant factory scenario.

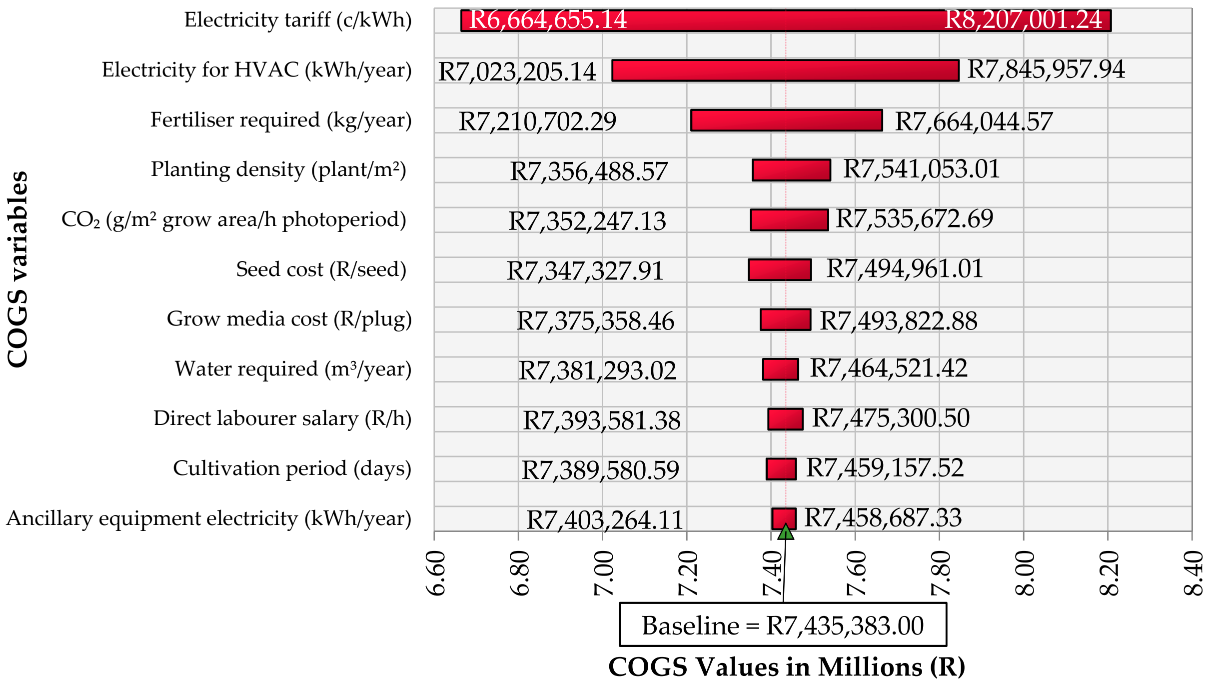

Figure S7. The sensitivity of cost of goods sold (COGS) values for the tobacco–transgenic (TT) plant factory scenario.

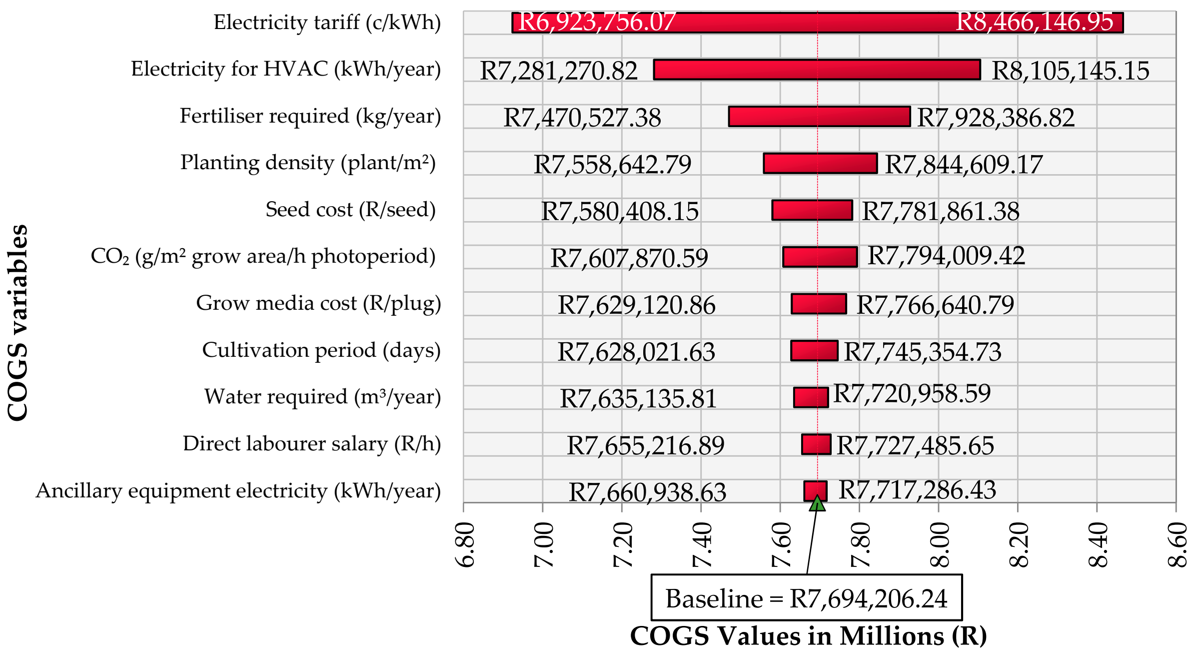

Figure S8. The sensitivity of cost of goods sold (COGS) values for the tobacco–transgenic-dwarf (TTD) plant factory scenario.

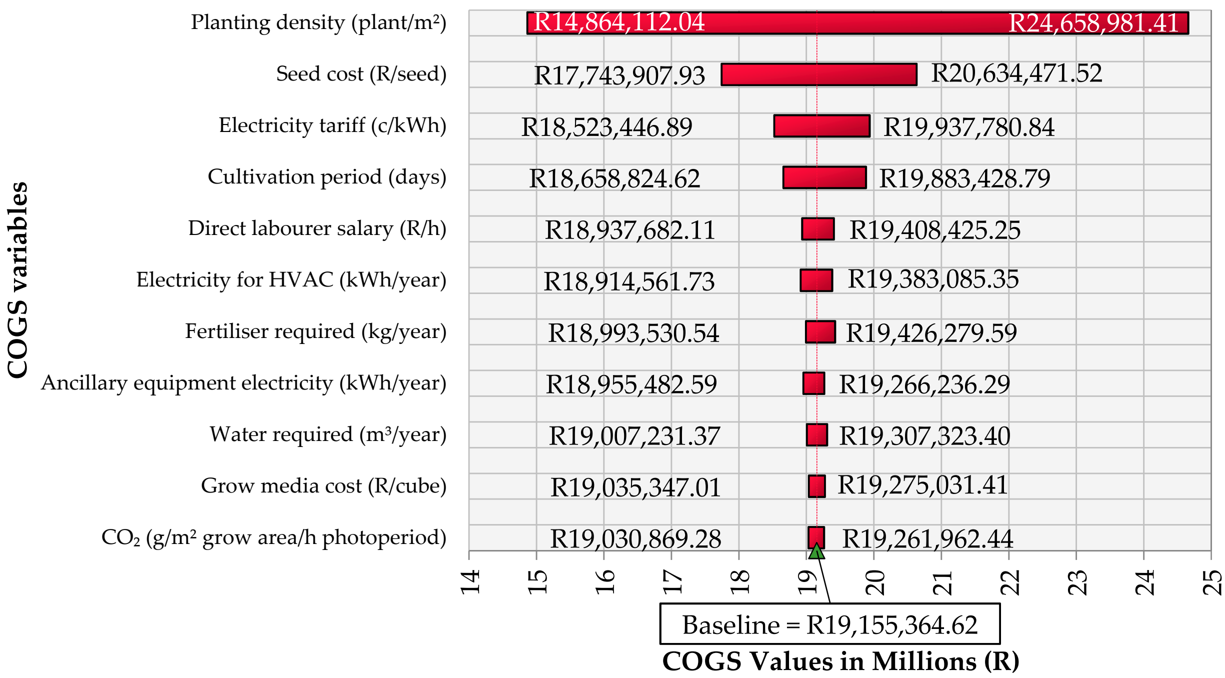

Figure S9. The sensitivity of cost of goods sold (COGS) values for the cannabis–conventional (CC) plant factory scenario.

7. Plant factory economic analysis market values and yield results

The primary product yields and associated market prices for TF and TM are shown in Table S19. Yields were obtained from the simulated scenarios and market prices were obtained from literature. The revenue from selling edible tomatoes in TF was evaluated using open-field producer prices and hydroponic selling prices to show the need of asking a premium for biomass that was cultivated in plant factories.

Table S19. Tomato-based plant factory yields and market values

Scenario	Description	Unit	Values	References
TF	Tomato fresh weight	kg/year	110,883 – 159,864	-
TF	Tomato producer price	R/kg	7.76 – 11.64	[155,156]
TF	Tomato hydroponic price	R/kg	27.00 – 82.00	[157–159]
TM	Tomato fresh weight	kg/year	63,017 – 108,351	-
TM	Miraculin accumulation in transgenic tomatoes	g miraculin/kg tomato fresh weight	0.617 – 0.978	[160]
TM	Miraculin from miracle berry price[a]	R/kg miraculin	59,400,000 – 89,100,000	[147,148]
TM	Miraculin sugar equivalent price[b]	R/kg miraculin	290,481 – 376,830	[149]

[a]Miraculin value was determined based on miracle berry market value [147,148] and assuming that miracle berry value was related to the miraculin accumulation levels [160] found in literature.
[b]Miraculin price based on sugar market value and miraculin:sucrose weight ratios to induce the same sweetening effect.

The lettuce yields and market selling prices for edible lettuce and accumulated miraculin are shown in Table S20. All the lettuce scenarios used the same plant factory grow area and had the same lettuce yields.

Table S20. Lettuce-based plant factory yields and market values

Scenario	Description	Unit	Values	References
LF/LM/LRI	Lettuce fresh weight	kg/year	96,294 - 249,464	-
LF	Lettuce producer price	R/kg	6.24 – 9.36	[156]
LF	Lettuce hydroponic price	R/kg	100-130	[161,162]
LM	Miraculin accumulation in transgenic lettuce	g miraculin/kg tomato fresh weight	0.03 – 0.04	[163]
LM	Miraculin sugar equivalent price[a]	R/kg miraculin	290,481 – 376,830	[149]

[a]Miraculin price based on sugar market value and miraculin:sucrose weight ratios to induce the same sweetening effect.

The biomass yields, value-added product yields and market prices for the products of each tobacco scenario are shown in Table S21. This data was used to calculate the revenue results of the tobacco scenarios. Tobacco fresh weight and methane were considered as two primary products of TC. Revenue derived from biodiesel production was considered a supplementary revenue stream as it was produced from tobacco seeds which is typically not harvested [164]. Extractable artemisinin was also considered supplementary as it has been investigated as a value-added product to help lowering the cost of biofuel production [93].

Table S21. Tobacco-based plant factory yields and market values

Scenario	Description	Unit	Values	References
TC	Tobacco fresh weight	kg/year	49,863- 63,485	-
TC	Tobacco producer price	R/kg	41.39 - 56.61	[156]
TC	Biodiesel yield[a]	kg/year	507 - 645	[164,165]
TC	Biodiesel price	R/kg	7.87 – 10.88	[166]
TC	Methane yield[b]	m^3/year	5,734 - 9,122	[165,167]
TC	Methane price	R/m^3	3.09 – 4.34	[166]
TC	Artemisinin accumulation in transgenic tobacco[c]	g artemisining/kg tobacco fresh weight	0.144 – 0.154	[168]
TC	Artemisinin price	R/kg	3,164 - 14,244	[93]
TPHB	Tobacco fresh weight	kg/year	23,235 - 35,786	-
TPHB	PHB accumulation in transgenic tobacco[d]	kg PHB/kg fresh weight tobacco	~0.03	[143]
TPHB	PHB price (polypropylene equivalent)	R/kg	16.67 – 18.97	[169]
TPHB	PHB price (PHB specific)	R/kg	62.71 – 85.78	[170]
TT	Tobacco fresh leaf weight[e]	kg/year	10,626 - 16,171	-
TT/TTD	HBV antibody accumulation levels in transgenic tobacco	kg HBV/kg fresh weight tobacco leaves	$2.73 \times 10^{-7} – 4.25 \times 10^{-7}$	[144]
TT/TTD	HBV antibody price	R/mg	6,907 – 8,639	[171,172]
TTD	Tobacco fresh leaf weight[e]	kg/year	11,709 - 16,943	-

[a]Biodiesel yield based on tobacco seed content 3 wt% of total fresh weight [165] and 2.95:1 seed to biodiesel conversion ratio on mass basis [164].
[b]Methane based on 101-169 m^3/ton feedstock conversion ratio [165,167].
[c]Artemisinin accumulation based on reported yields in dry weight tobacco [168] and an assumed 75% moisture content of fresh weight tobacco.
[e]PHB accumulation based on reported yields in dry weight tobacco [143] and an assumed 75% moisture content of fresh weight tobacco.
[e]Only leaf weight considered as the transgenic tobacco plants were small and HBV antibody accumulation was considered in the leaves only.

The cannabis biomass yields and market values for CC are shown in Table S22. The primary products were assumed to be the leaves and inflorescences of the whole plant and all further economic analyses were formed with the tabulated leaves and inflorescences biomass yields.

Table S22. Cannabis-based plant factory yields and market values

Scenario	Description	Unit	Values	References
CC	Cannabis whole plant fresh weight	kg/year	13,104 - 55,238	-
CC	Cannabis leaves and inflorescences fresh weight[a]	kg/year	3,931 - 16,571	[173]
CC	Cannabis fresh weight price[b]	R/kg	10,469 – 15,919	[174,175]

[a]Leaves and inflorescences yield assumed as 30% of whole plant fresh weight yield.
[b]Based on reported dry weight prices and an assumed moisture content of 75%. Reported dry weight prices assumed to include only leaves and inflorescences.

8. Plant factory economic analysis supplementary results

This section provides results from the economic feasibility evaluation of the investigated plant factory scenarios which was not included in the main body of research.

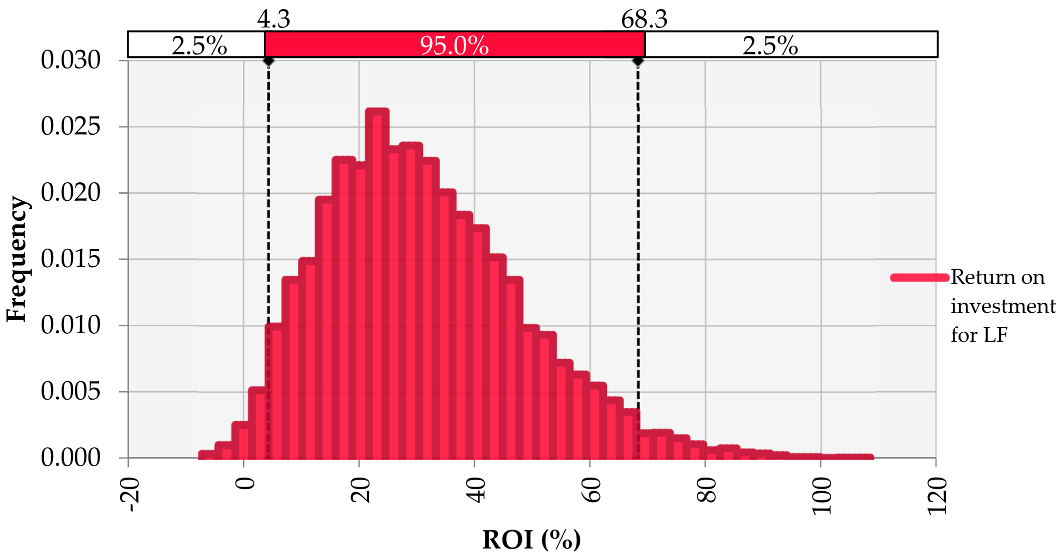

Figure S10. Probability density distribution of the return on investment (ROI) for lettuce–food (LF) scenario based on hydroponic pricing.

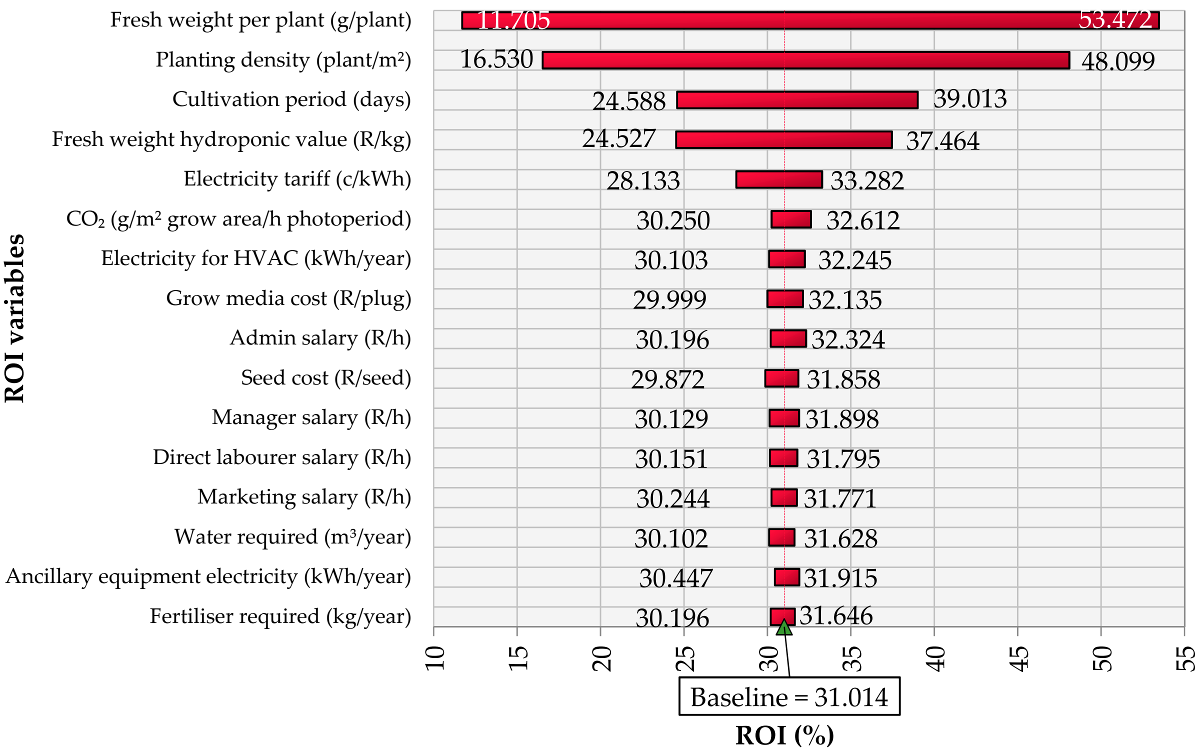

Figure S11. The sensitivity of return on investment (ROI) for the lettuce–food (LF) plant factory scenario.

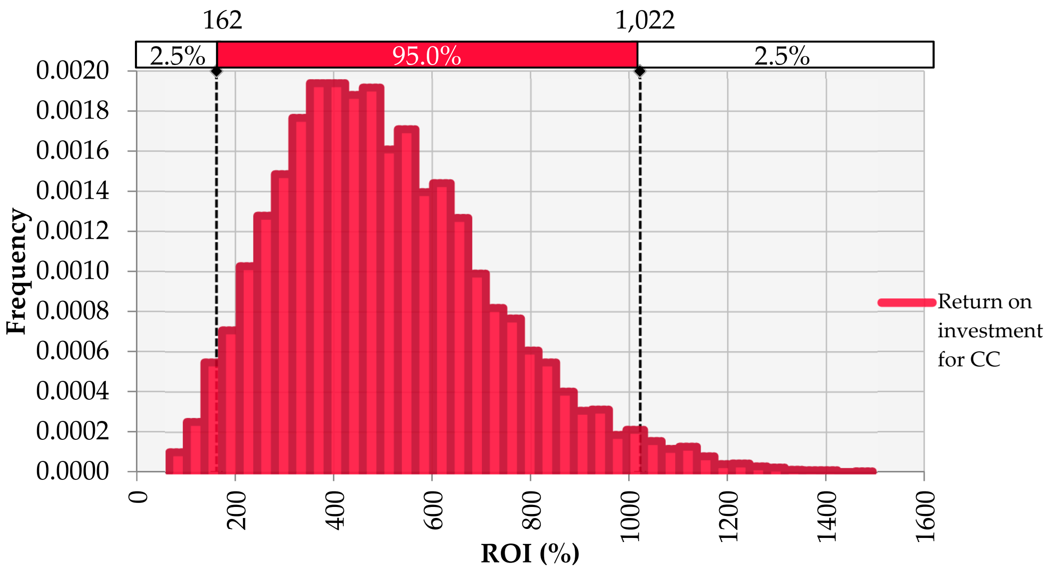

Figure S12. Probability density distribution of the return on investment (ROI) for cannabis–conventional (CC) scenario based on hydroponic pricing.

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