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

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Abstract: The use of a plant factory is typically associated with the cultivation of edible biomass for local markets within the urban environment and leads to economic feasibility being evaluated in this context. This paper explored the use of plant factories to produce biomass and value-added compounds for the biorefining industry to help frame the debate regarding the expansion of plant factory applicability to the greater biorefining value chain. Information regarding plant factory technology, crop selection for biorefining markets, and the industrial integration potential of plant factories was used to evaluate the economic feasibility of theoretical plant factory scenarios. From these scenarios, it was shown that plant factories showed economic feasibility while serving the food market and had significant potential in the biopharmaceutical market when accumulating adequate levels of biopharmaceutical products within the plants grown in the plant factories. These results suggested economic feasibility beyond the food market by selecting appropriate crops, based on plant factory and end-user market demands, and value-added compounds which could be accumulated in economically viable quantities.

Keywords: plant factory; controlled environment agriculture; biorefining industry; economic feasibility; value-added; biomass markets

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1. Introduction

The use of controlled environment agriculture (CEA), with plant factories being technologically complex variants of CEA structures, has shown significant improvements in crop yields, over open-field systems, by controlling environmental conditions to provide optimal growth rates for crops [1]. Together with increased crop growth rates, improved resource use efficiencies were also noticed in terms of water and fertiliser demands within plant factories [2]. Plant factories can also be used to address the mismanagement of land, as the structures do not require fertile land to be productive and can be constructed on marginal lands [3]. Plant factories can also form part of the bioeconomy as they use renewable biological resources to cultivate biomass which can be used to produce bio-based products [4]. Despite these benefits, the use of plant factories has remained limited. The use of a plant factory is typically associated with an expensive indoor cultivation system which requires significant capital investments and energy demands for artificial lighting and environmental control systems [2]. Due to these limitations, plant factories have been used primarily for the cultivation of edible biomass in the urban environment, and it is in this context which the relevance and economic feasibility of plant factories are discussed in the literature [5–8]. Plant factories that produced edible biomass were used to evaluate the energy efficiency of plant factory structures [5], to discuss the use of land for urban agriculture [6], to design urban agriculture structures [7], and to develop decision support systems for operating urban agriculture systems [8]. The constraint of only considering edible biomass as viable plant factory products ultimately limits the market potential of plant factory projects to that of food production.

The study of biomass cultivation within plant factories already consists of a significant body of knowledge in the literature where various aspects of plant factories are evaluated. This includes research into location selection [6,9,10], technological interventions to improve productivity and resource use efficiencies [11–13], energy demands of plant factories [5,14,15], environmental impacts and industrial symbiosis potential [16,17], and economic analyses to evaluate the financial viability of plant factory projects [7,8,18]. As mentioned earlier, various aspects of plant factories can be researched, but it is typically assumed that edible biomass is cultivated within these systems. Examples of this include Zeidler, Schubert, and Vrakking [7] who designed a vertical farm to cultivate lettuce and tomatoes by considering all the relevant constituent elements of the plant factory structure which influenced crop growth and resource use efficiency. Li et al. [8] developed a decision support system to help with the design and operation of urban agriculture structures. Although variations of urban agriculture structures and scenarios were evaluated using the decision support system, all the scenarios were based on producing edible biomass for the surrounding urban environment. Baumont de Oliveira et al. [18] stated that any crop could theoretically be cultivated within a plant factory and that the limiting factor was economic viability, rather than technical feasibility. This sentiment was also reinforced by the fact that the overwhelming majority of indoor cultivation studies have focused on edible leafy green biomass [13].

Despite the abovementioned research, not much has been written regarding the leveraging of crop growth rates and environmental control within plant factories to produce biomass for markets beyond the food market. Additionally, regarding plant factories as isolated systems diminishes its role within its surrounding economic environment. The economic relevance of plant factories can be improved by broadening the market potential of biomass grown in these facilities and by integrating plant factories more efficiently with the surrounding environment to improve overall economic viability. Through this approach, plant factories can contribute towards the sustainability discourse by focusing on changing production patterns and industrial development, respectively.

1.1. Knowledge Gap in Literature

A research opportunity was identified to increase the economic relevance of plant factory facilities beyond that of typical food cultivation. This opportunity was based on the concept of leveraging the crop growth performance, the resource use efficiencies [2], and the enhanced levels of environmental control [13] of plant factories to grow biomass for markets which were able to benefit from these properties. Therefore, the application of plant factories within the biorefining industry was of interest, as this opened the possibility of growing multiple crops with multiple potential value-added compounds for the biorefining markets. In this paper, the biorefining industry referred to any process or market that made use of biomass feedstocks to produce bio-based products. This broad definition was adopted to help identify markets ranging from biofuels to biopharmaceuticals, as an example. Expanding the use of plant factories to the greater biorefining industry required the exploration of new interpretations of the plant factory system boundary, the viability of plant factory crops based on crop growth performance and value-added compound accumulation, and the role of a plant factory in the economy.

1.2. Research Aim and Structure

The aim of this paper is to explore the use of plant factories as a biomass cultivation method within the greater biorefining value chain by evaluating the economic viability of biorefinery products and end-product markets, outside the food industry, that can make use of plant factory infrastructure as a biomass cultivation method. This paper does not aim to develop a novel method for evaluating the economic feasibility of plant factories and, as such, uses previously established methods. Instead, this paper explores the economic feasibility of novel theoretical plant factory scenarios which are not constrained by the economic potential of the food market for the produced products within plant factories.

This paper proposes, motivates, evaluates, and discusses the economic viability of using a plant factory to produce biomass under different theoretical scenarios. The scenarios are defined in terms of the technology being used within the plant factories, the end-user markets, crop selection, value-added compounds being accumulated in the biomass, and the use of industrial integration to lower operating costs. This knowledge is combined with previously developed decision support systems for urban farming [8,10] to model and evaluate the proposed plant factory scenarios in terms of expenses and the maximum revenue potential obtainable from the produced biomass. This paper shows the economic potential of plant factories when cultivating crops which accumulate value-added compounds in sufficient quantities and specifically highlights the potential of the biopharmaceutical industry to take advantage of plant factory infrastructure.

The aim of this paper is addressed by answering the research questions below:

- What are the main drivers and variables to consider during an economic feasibility evaluation of plant factory projects that produce feedstocks for biorefining processes?
- What is the economic feasibility for the use of plant factories to produce biomass feedstocks for the biorefining industry?

Section 2 describes the literature review which was conducted to define a plant factory system boundary which was not constrained by end-user market assumptions, and which could be used to accurately define and cost plant factory scenarios. Section 3 presents the overall methodology used to define and evaluate novel plant factory scenarios which produce biomass and value-added compounds for markets beyond the food market. Section 4 provides the economic results of the simulated plant factory scenarios. Section 5 discusses the implications and limitations of the paper, and Section 6 concludes the paper.

2. Literature

In this section, the results of a preliminary literature review of plant factory knowledge are summarised. The related plant factory works are categorised according to the main objectives of the studies, along with the crop selection which was made to fulfil the objectives. This was performed to illustrate the research gap of evaluating plant factories in terms of their viability in markets beyond the food market. The second half of this section shows the literature review which was conducted to establish a comprehensive plant factory system boundary, which could be used to guide the economic feasibility assessments of plant factories without being constrained by market limitations. The system boundary is used in Section 3 of this paper to define and assess novel plant factory scenarios.

2.1. Literature Review of Existing Plant Factory Knowledge

Table 1 shows the different types of the plant factory literature which were consulted in identifying the knowledge gap in crop- selection and data. The economic modelling literature all had different plant factory scenarios and objectives defined for their analyses. This included detailed designs of modular vertical farms [7], uncertainty analysis of case study plant factories [18], the development of decision support systems to help with decision-making when designing new plant factories, and the assessment of plant factories on the supply chain level [9]. Despite the varying scenarios and economic modelling methods, the crop selection remained limited primarily to leafy greens and herbs.

Table 1. Literature review of existing plant factory knowledge.

Article Type	Objective	Selected Crops	References
Economic modelling	Design of an economically feasible modular vertical farm	Lettuce and tomatoes	[7]
	Assessing financial risk of vertical farms using imprecise probability	Lettuce	[18]
	Development of a decision support framework to help design and operate urban farming systems	Leafy greens	[8]
	Development of a vegetable supply chain in the urban environment using plant factories	Leafy greens	[9]
Resource/ technology reviews	Quantify and compare resource requirements of greenhouses and plant factories	Lettuce	[14]
	Review of technology options available to greenhouses and plant factories	Lettuce and tomatoes	[11]
	Review of Internet of Things (IoT) solutions to monitor edible crop growth in vertical farms	Edible biomass, mostly leafy greens	[13]
	Review of differences in energy efficiencies between plant factory technology solutions	Edible biomass	[5]
	Review of controlled environment agriculture case studies in terms of challenges and opportunities	Leafy greens	[19]
	Review of the resource use efficiencies within plant factories	Leafy greens, highlights lack of larger crop growth data	[20]
Plant factory integration	Evaluating the industrial symbiosis of plant factories with surrounding industries	Leafy greens and herbs	[21]
	Evaluating the industrial symbiosis of plant factories with surrounding industries based on environmental impact measurements	Leafy greens and herbs	[16]
	Evaluating the integration of plant factories with on-site composting infrastructure	Lettuce	[22]
Plant factory assessments	Assessing the environmental, economic and social impacts of urban agriculture	Edible biomass	[23]
	Assessing the role of IoT technology within a plant factory case study	Lettuce	[24]
	Assessing the environmental impact of the constituent elements which make up a plant factory structure and business	Edible biomass	[25]

The technology review literature of plant factories showed similar limitations in crop diversity. Evaluating the impact of technology differences between greenhouses and plant factories requires adequate crop data from both versions of CEA structures. This has led to comparison articles of CEA structures using well-known crops, such as lettuce [11,14]. Similarly, it was concluded that research which focused on the impact of technology solutions within plant factories only used well-known plant factory crops to avoid additional complexity and to place the technology impacts in the context of available crop data [5,13,19,20].

Plant factory integration research was concerned with placing the plant factory within the greater economy by highlighting interactions with surrounding industries [21], and by assessing the impact of plant factory industrial symbiosis on economic and environmental levels [16,22]. There was also no specific focus on expanding the crop selection options for plant factories within the cited plant factory integration literature.

Lastly, the plant factory assessment literature assessed plant factories based on environmental, economic, and social impacts through literature reviews and surveys [23].

Specific assessments were also linked to case studies of technology selection [24] and the environmental impact of plant factory operations [25]. The literature review showed that multiple approaches have been used to investigate plant factories, each with their own objectives, and that none of the studies specifically considered an expansion of the crop selection process for economically viable plant factories. The next section shows the literature review which was conducted to develop a plant factory system boundary which has not yet been limited to the food market.

2.2. Literature Review for the Establishment of a Plant Factory System Boundary

This paper used a holistic approach to describing a plant factory system boundary. This was performed through a structured literature review that identified the important constituent elements which had to be considered for the economic feasibility evaluation of plant factories that serviced the biorefining industry. The initial investigation into plant factory projects [11] elucidated the potential for considering a system boundary which extended beyond the physical plant factory. The inputs and outputs of the physical structure were assumed to be part of the broader plant factory system boundary and were considered part of the plant factory supply chain. This paper drew on previous work regarding supply chain development for industries with large uncertainty [26], along with the literature concerned with CEA operations [2,8,11] and biorefining markets [27] to identify the main constituent elements of a plant factory system boundary. Therefore, the main research themes that emerged during the initial literature review included plant factory designs and operations, the alternative market potential that the biorefining industry offered to plant factory projects, and the supply chain considerations when introducing plant factories into the biorefining value chain.

These initial research themes are summarised in Table 2 and were expanded into more detail by using the literature search algorithm in Figure 1.

Table 2. Main research themes identified based on the literature review.

Key Research Themes	References
CEA/Plant factory design and operation	[1,2,8,11,28–34]
Supply chain under uncertainty	[9,26,27,35–41]
Biorefining markets	[27,42–52]

A structured literature search was used to expand on the key themes identified in Table 2. Each theme was researched in detail by dividing it into key terms. The Scopus database was used primarily, and all searches were performed using article title, abstract, and keywords to search for the desired terms. Document and access type were set to 'All', and published was set from 'All years' to 'Present'. The search algorithm is illustrated in Figure 1, and the expanded key themes are summarised in Tables S1–S3 in the Supplementary Material document. The literature which was consulted was not limited to plant factory studies, but correlations were found between the reported literature and the broader interpretation of plant factory system boundaries in this paper.

The expanded key themes in Tables S1–S3 were used to develop the plant factory system boundary shown in Figure 2.

The drivers and variables which were identified in the literature review were consolidated and are represented as a conceptual model in Figure 2 to correlate these considerations to capital expenditure (CAPEX), operating expenditure (OPEX), and revenue indexes. Figure 2 provides a framework for the economic assessment of plant factories at an industry level by highlighting considerations related to infrastructure design and operations, the expansion of plant factory revenue streams by considering alternative biomass markets, and by considering a plant factory as an open-loop system with interactions between the system and the surrounding environment. This conceptual model was used to define and describe novel plant factory scenarios to be evaluated for economic feasibility.

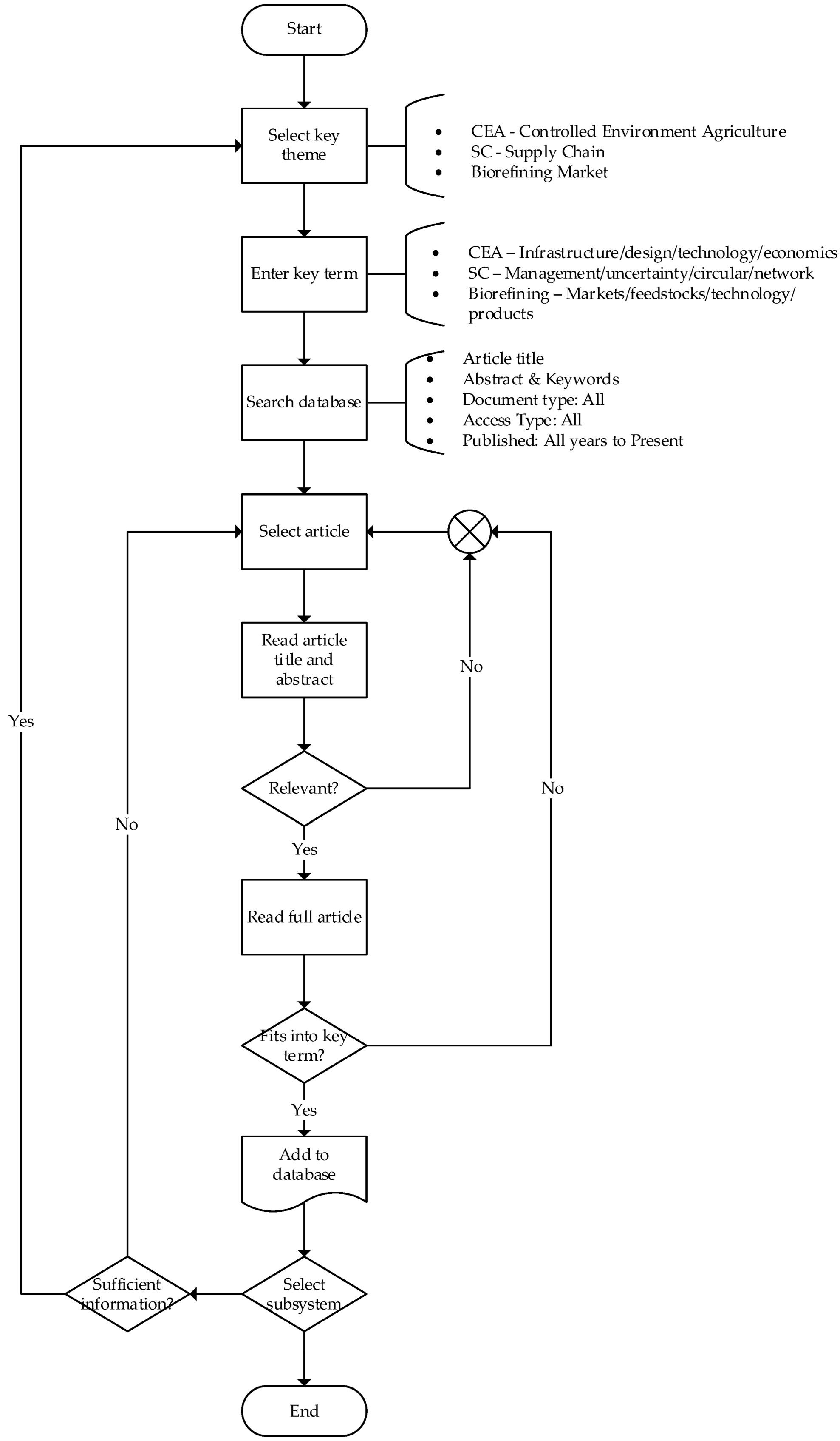

Figure 1. Literature search algorithm used to expand on the key research themes of plant factory system boundaries.

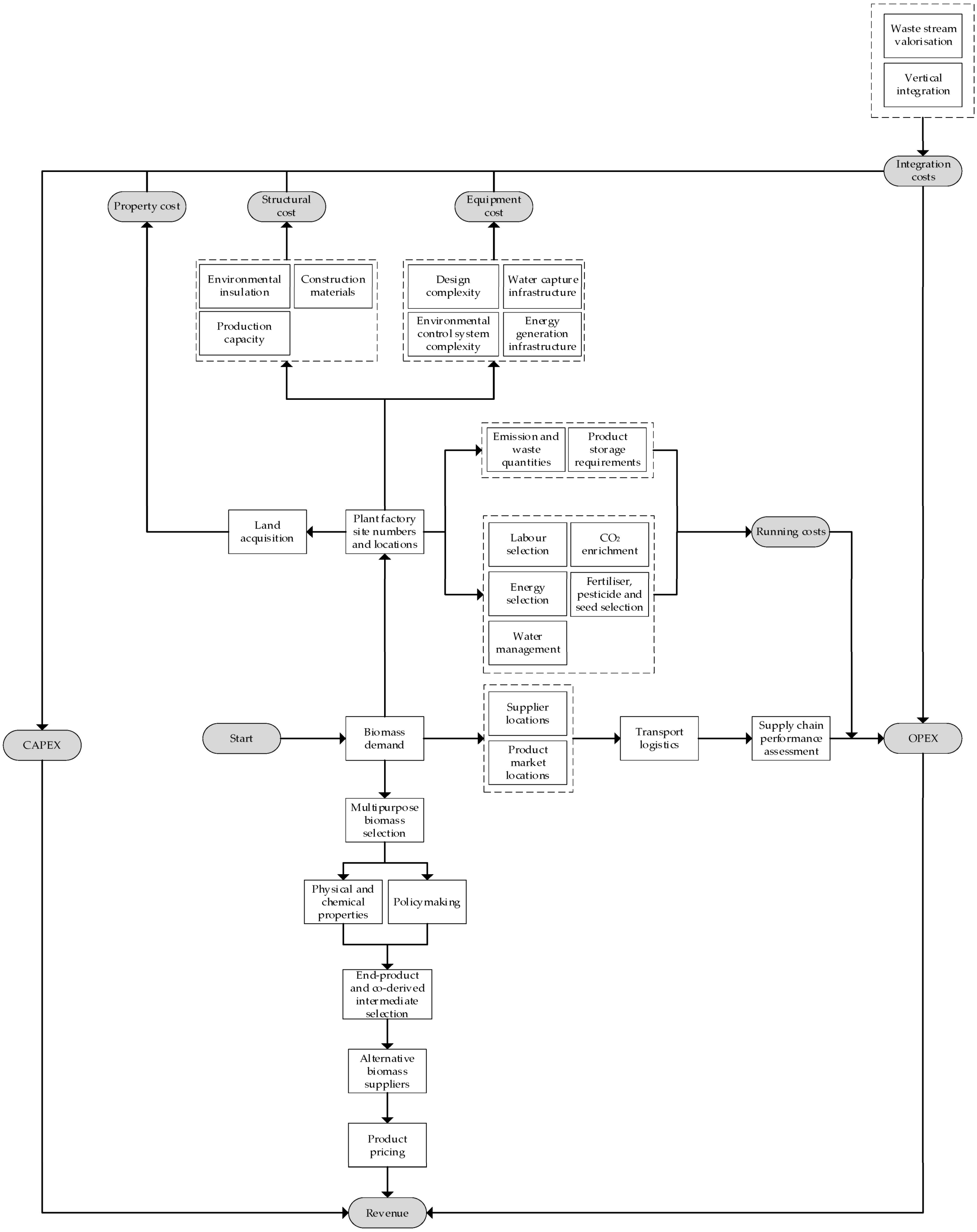

Figure 2. Correlating plant factory system considerations to CAPEX, OPEX, and revenue calculations.

3. Methodology

This section presents the steps which were taken to define, describe, and evaluate novel plant factory scenarios which produced biomass and value-added compounds for the biorefining industry. Firstly, the conceptual model in Figure 2 was used to identify the main components of a plant factory scenario which had to be defined. These components included plant factory structural designs, equipment selection, market selection, crop identification for biorefining markets, value-added compound identification and pairing with appropriate host plants, and the identification of plant factory industrial symbiosis opportunities.

Secondly, the theoretical plant factory scenarios of interest were defined and motivated for their inclusion into the exploration of the use of plant factories beyond the food market. Lastly, the selected economic modelling method, data acquisition, and data processing steps were explained to provide insight into how the plant factory scenarios were evaluated for economic feasibility.

3.1. Plant Factory Scenario Descriptions

A range of plant factory scenarios were proposed to be evaluated in terms of economic feasibility. Each scenario cultivated different crops and accumulated different value-added compounds for various markets within the biorefining industry. A plant factory with a constant 1000 m^2 footprint and floor-to-roof height of 4 m was assumed throughout all the scenarios. This resulted in a footprint and total growing area which was equivalent to other plant factory studies found in the literature [7,18]. The space breakdown within the plant factory also remained constant throughout all scenarios, as shown in Table 3, and resulted in a constant growing area of 600 m^2. An effective 60% growing area footprint was the most important footprint characteristic, as plant factories are unable to use the total footprint of the facility for cultivation [18,53]. The remaining footprint components were based on specifications and assumptions from the literature. The dimensions of the plant factory were kept constant for the scenarios so that the main variations between plant factory scenarios would be the selected crop, value-added compound, and variations in plant factory equipment needed to accommodate the crop cultivation.

Table 3. Plant factory footprint breakdown.

Plant Factory Component	Space Breakdown (%)	References
Germination and nursery	15	[54]
Growth phase bottom layer	60	[18,53]
Harvest, packaging, and storage	15	[30]
Walkways, offices, and ancillary spaces	10	Assumed
Total	100	-

Table 4 summarises the plant factory scenarios which were investigated. Most scenarios made use of vertically stacked horizontal grow racks which made up the entire 600 m^2 growing area footprint. All scenarios used artificial light-emitting diode (LED) lighting with no solar irradiation and used a hydroponic system to supply water and nutrients.

The scenarios described above had variations in crop selection, value-added compound accumulation, end-user markets, and plant factory configurations. The motivations for selecting the abovementioned scenarios are discussed below.

3.1.1. Crop Selection

Tomato was included in the tomato—food (TF) scenario for its presence in the plant factory literature [7,55], but it was selected primarily for the tomato—miraculin (TM) scenario, where transgenic dwarf tomatoes were successfully cultivated in plant factory chambers and accumulated significant amounts of the taste modifier called miraculin [56,57]. The TM scenario represented a novel use of plant factory cultivation to produce a value-added compound for the biopharmaceutical industry. Lettuce was chosen as a plant factory crop in the lettuce—food (LF), lettuce—miraculin (LM), and lettuce—renewable—integrated (LRI) scenarios as it is considered a viable baseline crop selection for plant factories. The successful cultivation of lettuce in plant factories is also reflected in the fact that it is commonly chosen as a research crop to investigate plant factory operations and productivity [13,14,24,58].

Lettuce-based scenarios were used as benchmark scenarios to confirm that the developed economic model was defined appropriately to show the economic viability of plant factories that produced leafy greens, as has been shown in the literature [7,8]. Tobacco was the selected crop for the tobacco—conventional (TC), tobacco—PHB (TPHB), tobacco—transgenic (TT), and tobacco—transgenic—dwarf (TTD) scenarios. Tobacco was chosen for its multiple revenue streams which included its baseline producer price value, its potential to accumulate anti-malarial artemisinin [51,59], polyhydroxybutyrate (PHB) [60], and plant-made pharmaceuticals, such as hepatitis B virus (HBV) antibodies [61,62]. Tobacco can also be used as a feedstock to produce bio-based products which include biomethane and biodiesel [63–65]. This meant that tobacco was a promising multipurpose crop and was used to explore the production of products for the biorefining industry. Cannabis was added for its well-known cultivation within a plant factory setting [66] and for its application in the biopharmaceutical industry [67]. The crop selections yielded crops which were suitable for the food market, biopharmaceutical market, biofuel market, and biopolymer market and allowed for the economic feasibility assessment to consider the appropriateness of plant factories for all these markets.

Table 4. Descriptions of scenarios being evaluated for economic viability using Monte Carlo simulations.

Scenario	Plant Factory Structure	Market	Products
Tomato—food (TF)	High-wire	Food	Edible tomatoes
Tomato—miraculin (TM)	Vertical farm (five levels)	Food/ biopharmaceutical	Miraculin accumulated in tomatoes
Lettuce—food (LF)	Vertical farm (five levels)	Food	Edible lettuce
Lettuce—miraculin (LM)	Vertical farm (five levels)	Food/ biopharmaceutical	Miraculin accumulated in lettuce
Lettuce—renewable—integrated (LRI)	Vertical farm (five levels)	Food	Edible lettuce, with solar panels and alternative fertiliser considered
Tobacco—conventional (TC)	Vertical farm (five levels)	Biopharmaceutical/ bio-based products	Tobacco biomass, accumulated artemisinin, biodiesel, and biomethane
Tobacco—PHB (TPHB)	Vertical farm (five levels)	Bio-based products	Polyhydroxybutyrate (PHB) polymer accumulated in tobacco
Tobacco—transgenic (TT)	Vertical farm (five levels)	Biopharmaceutical	Hepatitis B virus (HBV) antibodies accumulated in tobacco
Tobacco—transgenic—dwarf (TTD)	Vertical farm (five levels)	Biopharmaceutical	HBV antibodies accumulated in dwarf tobacco
Cannabis—conventional (CC)	Vertical farm (three levels)	Medicinal/recreational	Value in cannabidiol (CBD) content

3.1.2. Market and Product Selection

As mentioned earlier, the food market was included as the baseline biomass market as it is currently the most widely adopted market for plant factories and makes up a significant part of the available plant factory literature [9,68]. The inclusion of the food market also allows for the exploration of the economic feasibility of hydroponically cultivated food which is typically sold at a premium price for its freshness and lack of pesticides used during cultivation.

The biopharmaceutical market was included due to the revenue potential of accumulating high-value products in transgenic plants and the fact that the cultivation of the host plants benefit from the enhanced environmental control and insulation of plant factory systems [30,43]. Additionally, the large-scale production costs of transgenic plant cultivation and molecular farming is lower when compared to microbial fermentation systems and mammalian cell cultures [69]. Despite this, it still remains difficult to obtain specific production cost data of plant-made pharmaceuticals [70] and direct production cost comparisons across different platforms. This is partly attributed to the variations in techno-economic analyses used in the molecular farming literature [71]. Therefore, artemisinin and HBV antibodies were selected as biopharmaceutical products for their accumulation levels in host plants [59,62] and market value [51,72,73]. Miraculin was included for similar reasons [57,74], and represented recombinant proteins, instead of the typically investigated drug and vaccine products [56]. Miraculin has also been accumulated in host plants that are viable candidates for plant factory cultivation [74,75].

Lastly, bio-based products were included as alternatives to fossil-fuel products. The biopolymer PHB was selected for its accumulation levels in host plants that were suitable for plant factory cultivation [60] and it serves as an alternative product to polypropylene [76]. Additionally, biomass conversion into energy was considered in terms of biodiesel and biomethane production [65,77,78].

3.1.3. Technology and Integration Selection

The LRI scenario was selected to evaluate the economic impact of using renewable energy technology and integrating a plant factory with a surrounding industry. The importance of plant factory technology selection and industrial symbiosis from Figure 2 was represented in the LRI scenario. The energy cost of plant factories has been known to account for up to 30% of total operating costs [5] and one way of supplementing the energy demands, without requiring additional space, is through the use of photovoltaic (PV) panels being integrated onto the plant factory façade [5,79]. The LRI scenario will investigate to what extent the use of PV panels on the plant factory façade can supplement the high energy demands of the structure. Additionally, waste valorisation through industry integration was evaluated in the LRI scenario by considering the use of brewers' spent grains as growing substrate supplements [16,21,80]. The influence of the integration was evaluated in terms of potential cost reductions in growing media expenses in the LRI scenario.

3.2. Economic Modelling of Plant Factory Scenarios

The plant factory literature which considered economic feasibility used different approaches, but all had to define, scale, and cost the plant factory scenarios of interest to comment on the economic feasibility of the case studies. Zeidler, Schubert, and Vrakking [7] provided a detailed design of a modular vertical farming structure for the cultivation of leafy greens and tomatoes; Baumont de Oliveira et al. [18] used two well-defined plant factory case studies to investigate economic risks, while Thomson et al. [22] had to define and size a theoretical plant factory to comment on the economic benefit of integrating the structure with an on-site composting system. Based on this literature, it was decided to provide detailed costing information for the constituent elements of the plant factories. The system boundary of the economic analysis is shown in Figure 3.

Figure 2 was used, along with the plant factory literature, to provide the refined plant factory system boundary which showed the constituent elements of a plant factory which were included and excluded from further economic feasibility analyses [18]. The system boundary also indicated the exclusion of the variable downstream processing and extraction costs, to obtain the desired products, in each of the scenarios. Downstream processing steps were excluded from the system boundary for the sake of simplicity. This paper did not consider variations in extraction-, purification-, and conversion processes to obtain the desired products. Instead, the revenue potential of cultivated biomass and value-added compounds was calculated based on accumulation levels within the host plants, prior to any extraction processes. The methods used to quantify and process the CAPEX, OPEX, and revenue values in Figure 3 are discussed in Sections 3.2.1 and 3.2.2.

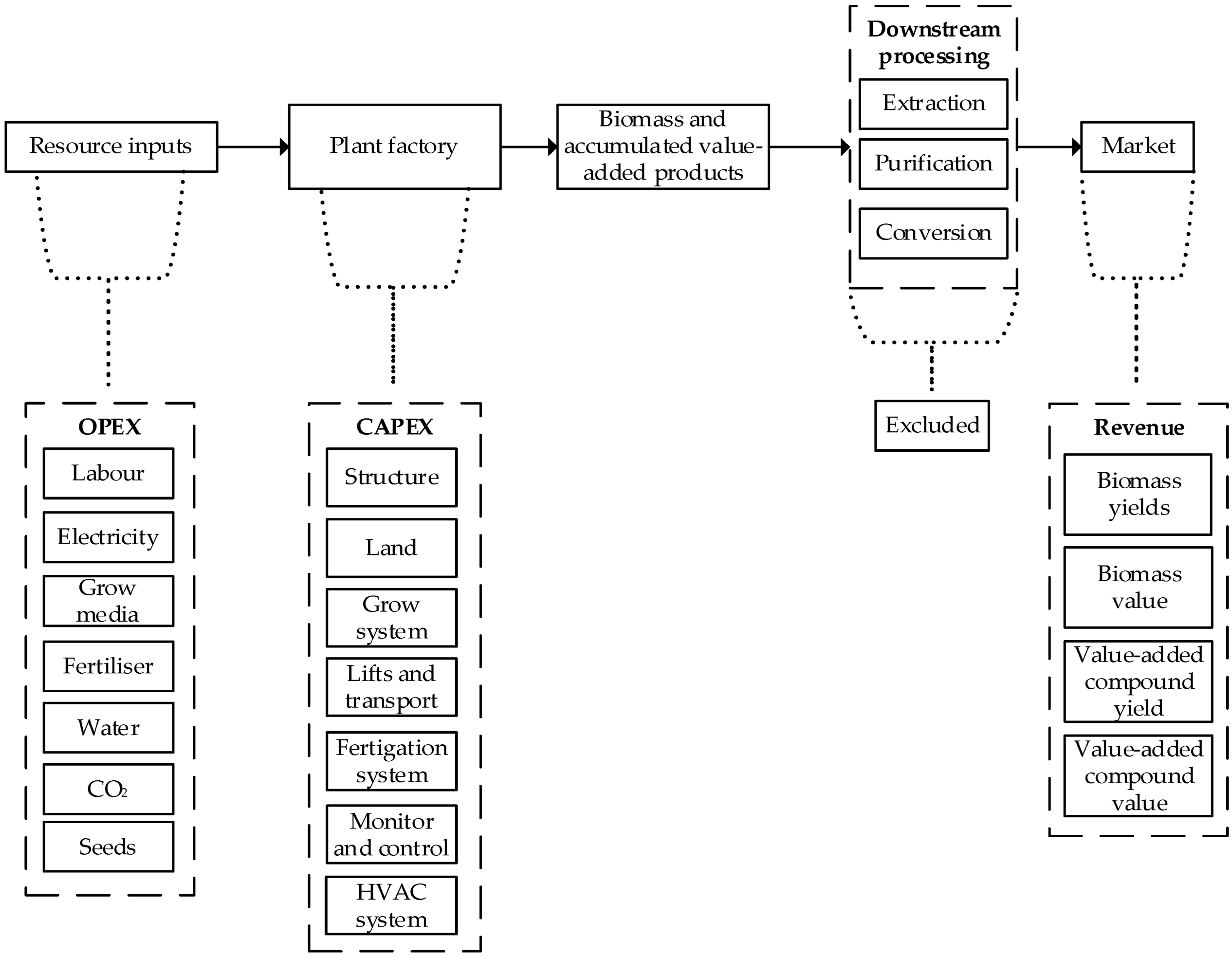

Figure 3. Plant factory system boundary for evaluating the economic feasibility of plant factory scenarios by calculating the cost of biomass cultivation and revenue potential of the produced products.

This paper had to define plant factory scenarios using the best-available data and assumptions. A full list of assumptions for the economic analyses is tabulated in Tables S4 and S5. Therefore, uncertainty analysis was used during the economic feasibility analysis of the investigated plant factory scenarios. Table 5 shows the literature which was consulted for the selection of Monte Carlo simulations.

Table 5. Literature review of economic modelling techniques.

Modelling Method	Objective	References
Monte Carlo	Economic risk assessment of biofuel technologies	[81]
Monte Carlo	Biomass supply chain development for biofuel production	[82]
Monte Carlo and System Dynamics	Review of greenhouse modelling techniques	[29]
Monte Carlo	Assessing economic viability of hydroponic cultivation in emerging markets	[83]
Probability bound analysis	Assessing financial risk of vertical farms using imprecise probability	[18]
Monte Carlo	Life cycle assessment (LCA) of biodiesel production from tobacco seeds	[65]
Monte Carlo	Sustainability assessment of bio-based aviation fuel	[84]

Monte Carlo simulations have found use in the CEA literature [29,83] and in biorefining studies [65,81,82,84]. Therefore, it seemed appropriate to use Monte Carlo sensitivity analysis in this paper which combined the research themes of plant factories and the biorefining industry. Baumont de Oliveira et al. [18] preferred the use of probability bound analysis to avoid making the necessary assumptions regarding the distribution shapes of input variables. This paper used a significant amount of the literature to populate plant factory input variables, and it was deemed acceptable to make the necessary assumptions to allow for Monte Carlo simulations to be used.

3.2.1. Data Acquisition

Data acquisition for the plant factory economic model was guided by the system boundary in Figure 3. In all instances, the literature was consulted to populate the economic model variables. The data were classified as (i) plant factory data, (ii) crop data, and (iii) biorefining market data. Plant factory data included structure costs, equipment specifications, and running costs, as summarised in the Supplementary Materials. Tables S6–S9 provides the literature values which were used to calculate the CAPEX values of plant factory scenarios. This includes plant factory footprint costs, grow rack costs, fertigation, and monitor and control infrastructure. Tables S10–S16 provides the OPEX values for the plant factory scenarios, as calculated using the literature values. This includes salary (fixed cost) values, LED lighting demand, electricity pricing, heating, ventilation and air conditioning (HVAC) demands, water, fertiliser, grow media, seeds, and CO_2 augmentation amounts. Tables S17 and S18 provide summarised plant factory dimensions and value-added compound pricing data, respectively.

Crop data consisted of optimal environmental conditions for crop cultivation, resource requirements, planting densities and biomass yields. The crop data literature, which was used to populate the economic model for each of the scenarios, is shown in Table 6 and in Tables S19–S22.

Table 6. Cultivation conditions for the plant factory scenarios.

	Growing Area	Planting Density	Biomass Yield per Plant	PPFD	Average Temperature	CO_2 Concentration	Photoperiod	Cultivation Period
	(m^2)	(Plant/m^2)	(g Fresh Weight/Plant)	(µmol/m^2/s)	(°C)	(ppm)	(h)	(Days)
Scenario								
TF	1020	2.5–2.8	20,320–30,480	600	22.5	1000	12	90–110
TM	2720	27–44	171–250	400	22.5	1000	12	70–90
LF	2720	32–66	80–200	200	17	1000	16	30–42
LM	2720	32–66	80–200	200	17	1000	16	30–42
LRI	2720	32–66	80–200	200	17	1000	16	30–42
TC	2720	3.6–4.8	~1700	275	27.5	750	13	100–130
TPHB	2720	32–44	67–101	275	27.5	750	13	90–110
TT	2720	26–39	43–59	275	27.5	750	13	74–84
TTD	2720	36–53	35–44	275	27.5	750	13	74–84
CC	1632	10–30	83–373	500	26	950	16	70–80

Lastly, the biorefining market data included biomass selling prices, value-added compound accumulation levels which were achievable in biomass, and value-added compound selling prices for revenue calculations. Tables S19–S22 summarise the plant factory yields and market values, based on reported values in the literature.

3.2.2. Data Processing

The CAPEX, OPEX, crop data, and market data which were acquired in Section 3.2.1 were tabulated in Excel spreadsheets. The raw data were processed into economic indexes for the plant factory scenarios by using the list of simulation model equations below [18].

Capital Expenditure (CAPEX) Calculations

The CAPEX value was divided into construction and equipment costs in Equation (1) to represent the costs of building a plant factory structure and furnishing it with the required equipment, respectively.

$$\text{CAPEX} = \text{Construction cost} + \text{Equipment cost} \tag{1}$$

The construction cost and equipment cost were expanded into more detailed calculations using Equations (S1)–(S3) in the Supplementary Materials.

Operating Expenditure (OPEX) Calculations

The OPEX costs consisted of fixed and variable costs, as shown in Equation (2). The fixed cost represents the yearly salary costs for indirect labour positions. Table S10 shows the fixed positions considered for the plant factory scenarios and the hourly salary wages assumed.

$$\text{OPEX} = \text{Fixed cost} + \text{Variable (COGS) cost} \tag{2}$$

The variable cost was expanded and calculated using the literature data and Equations (S4)–(S20) in the Supplementary Materials.

Economic Feasibility Calculations

Revenue calculations were based on the amount of saleable biomass being cultivated within the plant factory, the amounts of value-added compounds or potential biorefining feedstocks accumulated in the biomass, and the market value of the biomass, value-added compounds, and alternative biorefining products. The return on investment (ROI) was calculated using Equation (3) and calculated revenue, OPEX, depreciation, and CAPEX values. The payback period, inverse of ROI, was also calculated with Equation (4) to show how long it would take to recover the investment [8]. The tax and loan components were omitted from further consideration for simplicity.

$$\text{ROI} = (\text{Revenue} - \text{OPEX} - \text{Depreciation} - \text{Tax} - \text{Loan})/\text{CAPEX} \times 100 \tag{3}$$

$$\text{Payback period} = \text{CAPEX}/(\text{Revenue} - \text{OPEX} - \text{Depreciation} - \text{Tax} - \text{Loan}) \tag{4}$$

The cost of cultivation was also calculated using Equation (5) to comment on the required market price of plant factory products to maintain a certain level of profitability.

$$\text{Cost of cultivation} = (\text{OPEX} + \text{Depreciation})/(\text{Saleable product produced}) \tag{5}$$

This allowed for a yearly cultivation cost to be calculated for the plant factory and allowed the cost to be correlated to the yield of the plant factory product being produced with the cultivation cost. The economic model did not consider the downstream processing costs associated with the extraction, purification, and processing of the produced biomass to obtain the accumulated value-added products or to transform the biomass into bio-based products. The model only considered the cost of cultivating the specified host plant, feedstock, or edible biomass in a plant factory, and calculated the potential revenue based on accumulation levels and biomass yields reported in the literature. Capital for uncertainty was calculated for each of the plant factory scenarios using Equation (6).

$$\text{Capital for uncertainty} = \text{Revenue} - \text{Cost of cultivation} \tag{6}$$

This calculated the difference between revenue potential and the cost of cultivation. Capital for uncertainty was an indication of potential profits for each of the scenarios and showed the capital buffer available to absorb intermediate and downstream processing costs which were not included in the model.

The economic indexes were based on published biomass yields and value-added compound accumulation levels found in the specific crop literature. Monte Carlo simulations were performed using the acquired plant factory-, crop-, and market data. The referenced equations were used with input data as triangular distribution functions with the specified minimum, mean, and maximum values which were obtained in the literature. The Monte Carlo simulations were performed using the populated Excel spreadsheets and by using @Risk 8.2, which added Monte Carlo sensitivity analysis capabilities to Excel. The value ranges of the plant factory model input data reflected the uncertainty associated with the data. The economic model was simulated using 10,000 iterations for each of the plant factory scenarios to generate the economic indexes, which are reported in Section 4 of this paper.

4. Results

The plant factory scenarios were grouped together according to the biomass being produced within each scenario. The results were structured to show the cultivation conditions, and the CAPEX, OPEX, and revenue results of the theoretical plant factory scenarios which were being evaluated for economic feasibility. This allowed for the economic indexes of different scenarios to be compared directly to illustrate the effect of crop and product selection on the economic feasibility of the plant factory scenarios. Results included structural and equipment costs of the plant factories, cultivation conditions for each of the investigated crops, and breakdowns of the running costs and the overall economic potential of each scenario. Results were provided as value ranges with 95% probability. The differences in ROI, payback period, cost of cultivation, and capital for uncertainty were discussed in more detail to provide additional clarity to the calculated results. The plant factory descriptions for each of the scenarios are shown in Table S17.

4.1. Plant Factory Scenario Cultivation Conditions

The cultivation conditions for the tomato-based plant factory scenarios are summarised in Table 6. The growing area for the tomato high-wire system in tomato—food (TF) was based on the specified growing area footprint of the 1000 m^2 plant factory. Based on the specified high-wire rows and dimensions in Table S17, the vertical growing area of the TF scenario was estimated as 1020 m^2, while the five levels of vertically stacked horizontal growing trays in tomato—miraculin (TM) resulted in a total growing area of 2720 m^2. The planting densities [7,56,85], fresh weight per plant [7,86], photosynthetic photon flux density (PPFD) [5,56], cultivation temperature [55], desired CO_2 level, photoperiod [5], and cultivation days [57] were based on reported values in the literature. The economic feasibility of TF was evaluated for cultivating edible tomatoes within a high-wire plant factory facility, and all revenue potential was based on the market value of the edible tomatoes being produced. The TM scenario was evaluated for using transgenic dwarf tomatoes as a host system to accumulate miraculin [74]. The dwarf tomato plants allowed for high density cultivation in a vertical farming grow room, and the revenue potential was linked to the accumulation levels and market value of miraculin.

The lettuce-based scenarios operated under the same conditions with lettuce—food (LF) producing edible lettuce and lettuce—miraculin (LM) producing similar lettuce which accumulated miraculin. Lettuce—renewable—integration (LRI) also produced edible lettuce but used PV panels and brewers' spent grains to lower electricity demand from the grid [79] and use valorised waste material as grow media [8,16], respectively. The planting density, biomass yields [7,87], PPFD, temperature, CO_2 levels, photoperiod, and cultivation time [5,68,88] resulted in lettuce plants that were of sufficient size to be cultivated in a five level vertical farming plant factory module with a fixed floor-to-roof height.

Tobacco plant heights of less than 100 cm were used for all the tobacco-based scenarios while calculating annual biomass yields [62,64]. As a result, it was assumed that five levels of vertical growing area were viable within the confines of the 4 m high structure and resulted in a total growing area of 2720 m^2 for all the tobacco scenarios. The tobacco—conventional (TC) scenario was investigated for selling tobacco at producer prices, being used as biodiesel and biomethane feedstocks, and for accumulating the anti-malarial drug, artemisinin. The economic feasibility of tobacco—PHB (TPHB) was evaluated by considering the revenue potential of the annual PHB polymer accumulation within transgenic tobacco plants. The tobacco—transgenic (TT) and tobacco—transgenic—dwarf (TTD) scenarios both accumulated HBV antibodies and were compared to investigate the influence which genetic modification had on the profitability of plant factories. In this case, TT and TTD produced similar amounts of biopharmaceutical products per unit of biomass [62] but the dwarf tobacco plants in TTD resulted in more biomass being produced in a similar plant factory space. The PPFD, average temperature [89], CO_2 levels [90], and photoperiod [89,91] remained constant for all the tobacco scenarios. The planting density and cultivation period of TC was approximated using open-field data for larger plants [77,92], and the planting densities for TPHB, TT, and TTD were assumed to be similar to lettuce planting densities, as the tobacco plants were sufficiently small to fit into vertical farming infrastructure [60,62]. Cultivation period data for TPHB, TT, and TTD was obtained from the same literature as the planting densities to improve the accuracy of estimate annual biomass yields.

The growing area of 1632 m^2 for CC was less than the five level growing areas of 2720 m^2 in tomato, lettuce, and tobacco scenarios. The cannabis-based scenario used a plant factory with three levels, instead of five. This was decided as the typical indoor cannabis plant height was 100–140 cm [93] and would not fit into five levels of grow trays with a 4 m plant factory room height. The planting density, artificial lighting, average temperature, CO_2 levels, photoperiod, and cultivation period data were obtained from the literature which considered cannabis cultivation under plant factory conditions [5,66]. Although industrial hemp has shown to be a promising multipurpose crop [94], it was omitted due to a lack of large-scale cultivation data within plant factories and the marginal revenue potential of the multiple revenue stream approach in scenario TC. Instead, the economic potential of CC was determined by selling cannabis based on medicinal and recreational market uses [66,93].

4.2. Plant Factory Scenario CAPEX Results

The CAPEX results, for all the plant factory scenarios which were evaluated using the economic model in this paper, are shown in Tables 7 and 8. The structure cost did not change between the two tomato-based scenarios, TF and TM, but the cost differences between a high-wire system and vertical growing rack system were illustrated in the equipment costs. The plant factory module cost in TF was significantly less than the TM module. This was attributed to the fact that the TF high-wire CAPEX cost was estimated as a single level grow system while TM was costed as five levels of grow racks, which also gave it a significantly larger growing area in Table 6. The lower monitor and control system costs were also attributed to the differences in total growing area between the high-wire and vertical farming scenarios. The TF scenario required less equipment to maintain an adequate sensor density within the growing space. The lift and transport, fertigation system, and HVAC system costs were assumed to be similar between scenarios, as they were not the primary cost drivers of the CAPEX calculations and simplified further calculations.

The CAPEX of LF, LM, and LRI are shown with LF and LM sharing the same CAPEX values. The total CAPEX value of LRI increased from R27,659,880 to R30,709,880, and was attributed to the rooftop installation of PV panels onto the plant factory. The costs were added to the plant factory module cost component. The PV system cost breakdown is shown in Table 7 with a depreciation lifespan of 25 years [95]. Additional battery storage was not added to the system, as it was assumed that the electricity being generated from the system would be used on a continual basis and would not be stored.

Table 7. Photovoltaic (PV) panel system description.

	Quantity	Unit Price (R)	Total Component Price (R)	Depreciation Cost per Year (R/Year)
Panel (455 W rating)	500	3334	1,666,925	-
Inverter (8 kW)	22	43,413	955,075	-
Installation	-	-	428,000	-
Total CAPEX			3,050,000	122,000

Based on the provider details, the PV system could generate 37,538 kWh of electricity per month, or 450,456 kWh per year [95]. The impact which this system had on the COGS for the LRI scenario was discussed later in terms of energy cost savings.

The total CAPEX costs for the tobacco-based plant factory scenarios did not vary as the growing space and environmental conditions in Table 6 remained constant. The total CAPEX cost for the tobacco scenarios turned out to be the same as TM. The equipment costs were kept constant, as all the tobacco scenarios made use of five layers of vertical farming grow area. As a result, the plant factory module was the largest cost.

The CAPEX costs of R19,522,622 for scenario CC was significantly lower than the CAPEX of R27,659,880 for the tomato (excluding high-wire TF), lettuce, and tobacco scenarios. The lower CAPEX of CC was attributed to the reduction in vertical growing racks from five levels to three levels. This resulted in a lower plant factory grow module cost, and in a reduction in the monitor and control system cost. The smaller growing area of CC also required fewer monitor and control sensors to control the environmental parameters.

4.3. Plant Factory Scenario OPEX Results

The OPEX results for TF and TM remained a function of fixed costs and variable (COGS) costs. The calculated range of OPEX costs for TF and TM are tabulated in Table 9. The electricity costs made up significant portions of the total OPEX and were consistent with the literature which investigated plant factories with artificial lighting [5,7]. The individual components which made up the variable costs for TF resulted in a COGS range of R3,026,155–R4,033,157. The sensitivity analysis of the COGS value is shown in Figure S1, and shows that the COGS was most sensitive to electricity tariff changes, HVAC energy demand, and fertiliser requirements.

The COGS for TM, had a price range of R7,649,327–R9,904,036 and was more than double that of the TF. The high-density biomass cultivation of the vertical farming structure in TM led to planting density, fertiliser requirements, and seeds costs having a large effect on COGS, when compared to their influence on COGS for high-wire TF. This was also reflected in the sensitivity analysis shown in Figure S2.

The calculated OPEX for the lettuce-based scenarios are shown in Table 10 and Figure S3. The annual grid electricity cost for LRI was reduced from R3,969,748–R5,569,269 to R3,509,923–R4,955,137 by installing the PV system which is described in Table 7. This resulted in an annual electricity cost reduction of ~10%. Assuming brewers' spent grains were able to fully replace inert rockwool as a grow media, the annual grow media cost was reduced by almost 90% from R522,790–R1,064,527 to R71,693–R136,903. Calculations were based on replacing rockwool with volume-equivalent brewers' spent grains [16]. Table 10 also shows that the PV system and brewers' spent grains both lowered the total COGS values for LRI, and that the lowest annual COGS range of R4,990,546–R6,499,481 was achieved by implementing both strategies.

Table 8. Total CAPEX results for the plant factory scenarios.

	Scenarios	Cost (R)	Lifespan (Years)	Depreciation per Year (%)	Depreciation Cost per Year (R/Year)
Construction					
Structure	TF				
	TM				
	LF, LM, LRI	6,745,000	30	3.33	224,833
	TC, TPHB, TT, TTD				
	CC				
Equipment					
Plant factory module	TF	3,430,353	25	4	137,214
	TM	17,151,765	25	4	686,071
	LF, LM, LRI	17,151,765 20,201,765 [a]	25	4	686,071 808,071 [a]
	TC, TPHB, TT, TTD	17,151,765	25	4	686,071
	CC	10,291,059	25	4	441,642
Lift and transport car	TF				
	TM				
	LF, LM, LRI	100,000	15	6.67	6667
	TC, TPHB, TT, TTD				
	CC				
Fertigation system	TF				
	TM				
	LF, LM, LRI	328,720	10	10	32,872
	TC, TPHB, TT, TTD				
	CC				
Monitor and control system	TF	997,577	10	10	99,758
	TM	2,497,801	10	10	249,780
	LF, LM, LRI	2,497,801	10	10	249,780
	TC, TPHB, TT, TTD	2,497,801	10	10	249,780
	CC	1,546,739	10	10	154,674
HVAC system	TF				
	TM				
	LF, LM, LRI	836,595	10	10	83,660
	TC, TPHB, TT, TTD				
	CC	511,105	10	10	51,110
Total CAPEX	TF	12,438,245	-	-	585,003
	TM	27,659,880	-	-	1,283,882
	LF, LM, LRI	27,659,880 30,709,880 [a]	-	-	1,283,882 1,405,882 [a]
	TC, TPHB, TT, TTD	27,659,880	-	-	1,283,882
	CC	19,522,622	-	-	881,799

[a] The CAPEX results of the lettuce—renewable—integration (LRI) scenario which included rooftop solar panel installations.

Table 9. Total OPEX results for the tomato-based plant factory scenarios.

		Scenarios	
OPEX component	Unit	TF	TM
Fixed cost			
Indirect labour	R/year	1,499,273–1,820,279	1,499,904–1,819,928
Variable (COGS) cost			
Direct labour	R/year	44,831–102,254	67,267–153,381
Electricity	R/year	2,493,606–3,474,307	4,990,472–7,031,889
Water	R/year	27,762–56,661	74,026–151,092
Fertiliser	R/year	85,232–249,538	227,221–665,379
Grow media	R/year	28,556–41,144	190,344–331,501
Seeds	R/year	1,081–1,559	938,925–1,629,663
CO_2	R/year	190,498–260,537	507,981–694,757
Total COGS	R/year	3,026,155–4,033,157	7,649,327–9,904,036

Table 10. Total OPEX results for the lettuce-based plant factory scenarios.

		Scenarios		
OPEX component	Unit	LF	LM	LRI
Fixed cost				
Indirect labour	R/year	1,496,505–1,821,113		
Variable (COGS) cost				
Direct labour	R/year	67,263–153,384		
Grid electricity	R/year	3,969,748–5,569,269		3,509,923–4,955,137
Water	R/year	61,100–114,189		
Fertiliser	R/year	184,864–502,663		
Grow media	R/year	522,790–1,064,527		71,693–136,903
Seeds	R/year	59,815–120,663		
CO_2	R/year	677,290–926,297		
Total COGS	R/year	6,059,818–7,815,184		5,596,623–7,207,506 (panels) 5,454,366–7,112,600 (grains) 4,990,546–6,499,481 (combined)

The annual OPEX values for the tobacco-based plant factory scenarios are shown in Table 11, with the differences in COGS values for each of the tobacco scenarios illustrated in Figure S4. Most of the OPEX values remained constant throughout the tobacco scenarios, similar to the CAPEX results. Variability was only detected with the grow media and seed costs. This was attributed to the fact that each of the tobacco scenarios had varying planting densities and cultivation periods. This resulted in different amounts of tobacco plants being cultivated annually in each scenario, and the grow media and seed purchases had to correspond to the number of plants being cultivated each year.

As mentioned above, the variability in COGS results was also attributed to the different plant densities and cultivation periods of Table 6. The annual COGS values, at 95% probability, were R5,816,197–R7,840,108 for TC, R6,393,465–R8,434,953 for TPHB, R6,435,846–R8,488,624 for TT, and R6,692,149–R8,737,868 for TTD. The elevated COGS value for TTD was expected, as the planting density was the highest of the tobacco scenarios and the cultivation period was the shortest. This resulted in the largest number tobacco plants being cultivated in the TTD scenario, even though the low fresh weight per plant in Table 6 meant that TTD did not produce the most amount of biomass. The electricity cost and fertiliser requirements remained the two main cost drivers, and are shown in Figures S5–S8.

Table 11. Total OPEX results for the tobacco-based plant factory scenarios.

		Scenarios			
OPEX component	Unit	TC	TPHB	TT	TTD
Fixed cost					
Indirect labour	R/year	1,498,525–1,825,671			
Variable (COGS) cost					
Direct labour	R/year	67,257–153,381			
Electricity	R/year	4,452,982–6,392,575			
Water	R/year	69,922–163,230			
Fertiliser	R/year	219,298–719,451			
Grow media	R/year	16,655–26,054	173,400–268,689	185,156–294,406	253,819–399,207
Seeds	R/year	32,634–50,817	340,188–526,262	361,714–573,686	497,917–784,409
CO_2	R/year	550,339–752,628			
Total COGS	R/year	5,816,197–7,840,108	6,393,465–8,434,953	6,435,846–8,488,624	6,692,149–8,737,868

The OPEX breakdown for CC is shown in Table 12. The seed cost, R7,572,613–R18,710,626, made up the majority of the R14,152,192–R25,731,525 COGS. This was the only scenario which had seed cost as the main OPEX driver, and it pointed to the high retail value of cannabis plants [96].

Table 12. Total OPEX results for the cannabis-based plant factory scenario.

		Scenario
OPEX component	Unit	CC
Fixed cost		
Indirect labour	R/year	1,498,023–1,822,495
Variable (COGS) cost		
Direct labour	R/year	44,828–102,261
Electricity	R/year	4,664,240–6,433,889
Water	R/year	72,977–98,105
Fertiliser	R/year	216,546–427,402
Grow media	R/year	222,168–557,353
Seeds	R/year	7,572,613–18,710,626
CO_2	R/year	406,384–555,778
Total COGS	R/year	14,152,192–25,731,525

The value of the cannabis plant was also reflected in the sensitivity analysis of COGS in Figure S9. The main cost drivers were planting density and seed cost, with electricity tariff rates being third.

The planting density directly influenced the total cost of all the consumables required for optimal cultivation and had a cumulative effect on the COGS. Variations in planting density were also more impactful than cultivation period. This was attributed to the long cultivation period of 70–80 days [5,66] which meant that small variations in cultivation period did not have a significant impact on the biomass throughput of the plant factory.

4.4. Plant Factory Scenario Revenue Results

This section provides the calculated economic indexes for all the plant factory scenarios which were evaluated for economic feasibility. The market values of the produced biomass and value-added products, along with the calculated yields for each of the plant factory scenarios, are summarised in Tables S19–S22 in the Supplementary Materials. The tabulated values were used, along with Equations (3)–(6) to populate Table 13, which summarises the economic indexes for all the investigated scenarios.

4.4.1. Tomato-Based Plant Factory Revenue Results

The economic indexes for TF and TM are summarised in Table 13, as calculated using the market values and biomass yields in Table S19. For TF, the revenue obtained when selling tomatoes at the typical producer price was significantly lower than the annual cost of cultivation. This resulted in a negative average ROI of −36% and resulted in omission from further consideration. After considering the hydroponic tomato retail value of R27.00–82.00/kg, the annual revenue potential of TF went up from R1,010,876–R1,635,218 to R4,195,270–R10,599,920 and suggested improved economic viability by providing tomatoes directly to consumers, instead of accepting producer price rates. The ROI values of TF in Figure 4 shows the potential of making an annual loss, even when using hydroponic prices. Despite this, there was a 78% probability of making a profit and a 25% probability of making a ROI of 20% or greater.

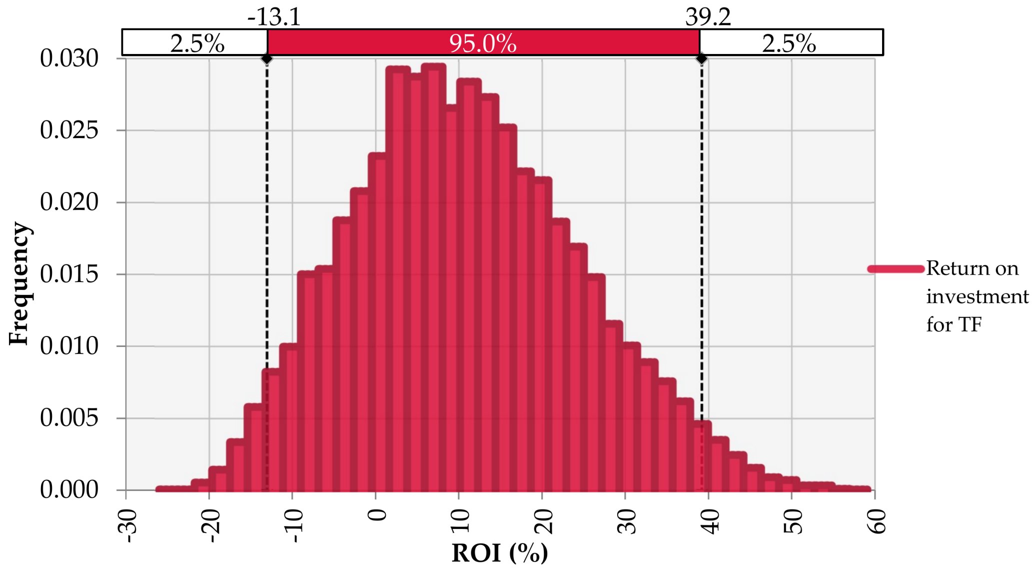

Figure 4. Probability density distribution of the return on investment (ROI) for the tomato–food (TF) scenario based on hydroponic pricing.

The sensitivity analysis, Figure 5, for TF shows that tomato prices, fresh weight yield, cultivation period, and electricity tariff changes had the most significant impact on ROI values [97]. The fresh weight yield and cultivation periods can be managed to some extent by controlling the environmental conditions within the plant factory, but the fresh weight value is dependent on market conditions. The sensitivity analysis showed that the production of high-value and high-yield products within the plant factory was more influential on profitability, compared to the electricity costs.

The annual capital for uncertainty, −R1,624,654–R4,871,751, in Table 13, represents the potential profits of the TF scenario and the capital available to absorb costs which were omitted from the system boundary of the economic model. For TF, these uncertainties included harvest losses, packaging costs, storage, transportation, and market demands at the specified hydroponic prices.

Table 13. Summarised economic indexes of all the plant factory scenarios.

		Scenarios									
	Unit	TF	TM	LF	LM	LRI	TC	TPHB	TT	TTD	CC
Revenue	R/year	1,010,876–1,635,218 (producer price) 4,195,270–10,599,920 (hydroponic price)	3,204,000,000–7,066,000,000 (miracle berry) 14,652,953–31,506,451 (sugar equivalent)	729,257–1,996,895 (producer price) 10,945,263–28,962,000 (hydroponic price)	1,081,285–3,011,150 (sugar equivalent)	729,257–1,996,895 (producer price) 10,945,263–28,962,000 (hydroponic price)	2,235,798–3,329,928 (producer price) 19,982–36,106 (methane) 4314–6521 (biodiesel) 26,086–120,392 (artemisinin)	12,564–19,870 (polypropylene price) 49,878–86,110 (PHB price)	25,231,351–48,806,539 (HBV antibody)	27,519,590–51,613,595 (HBV antibody)	50,999,614–225,340,789
Cost of Cultivation [a]	R/year	5,247,052–6,308,527	10,596,485–12,867,671	8,988,2645–10,783,088	8,988,2645–10,783,088	8,643,900–10,298,222 (panels) 8,389,501–10,065,881 (grains) 8,042,543–9,582,324 (combined)	8,743,519–10,795,692	9,325,878–11,383,441	9,371,340–11,435,940	9,620,235–11,701,874	16,702,559–28,286,586
	R/kg/year	35–53	108–184	40–101	N/A	38–97 (panels) 37–96 (grains) 35–91 (combined)	147–203	N/A	N/A	N/A	455–1,480 (whole plant) 1,516–4,935 (leaves and inflorescences)
ROI	%	−36 (producer price) 11 (hydroponic price)	17,600 (miracle berry) 37 (sugar equivalent)	−31 (producer price) 31 (hydroponic price)	−29	29 (panels) 33 (grains) 31 (combined)	N/A	N/A	93	101	508
Payback Period [b]	years	9 (hydroponic price)	0.006 (miracle berry) 3 (sugar equivalent)	3.23 (hydroponic price)	N/A	3.45 (panels) 3.03 (grains) 3.23 (combined)	N/A	N/A	1.1	1.0	0.20
Capital for uncertainty	R/year	−1,624,654–4,871,751 (hydroponic price)	3,031,137–19,655,509 (sugar equivalent)	1,194,202–18,899,854 (hydroponic price)	N/A	1,633,439–19,341,092 (panels) 1,738,310–19,692,730 (grains) 2,160,251–20,086,477 (combined)	N/A	N/A	14,870,937–38,352,675	16,888,055–41,009,508	31,597,483–199,523,749

Note—[a] Cost of cultivation was also calculated based on total saleable biomass being produced each year. [b] The tabulated values are the mean values obtained during Monte Carlo simulations. Here, N/A refers to values which were not calculated as the corresponding plant factory scenarios were omitted from further analysis due to poor economic indexes.

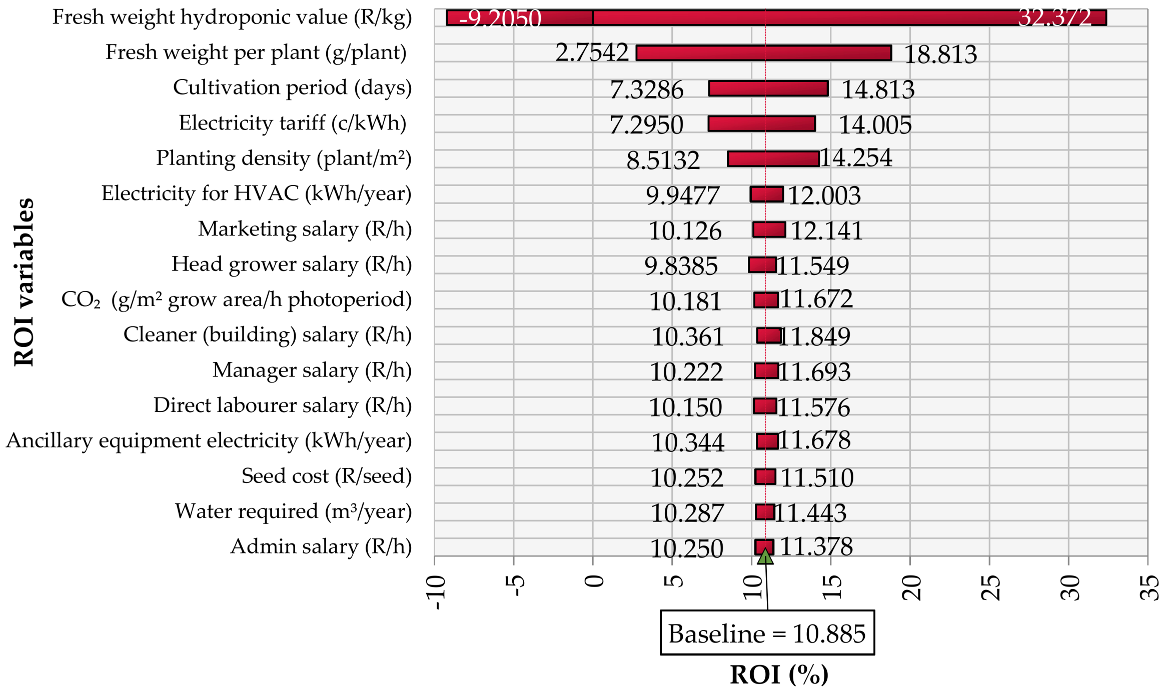

Figure 5. The sensitivity of return on investment (ROI) for the tomato–food (TF) plant factory scenario.

The profitability of TM was evaluated using two price estimates for the miraculin, in Table S19, that accumulated in transgenic tomatoes. Miraculin is not readily available in its pure extracted form and so its value was estimated by considering the market price of miracle berries, which naturally contain miraculin, and the miraculin accumulation levels in the miracle berries [57,98]. This resulted in a miraculin price range of R59 million–89 million/kg. Upon further investigation, it was found that recombinant miraculin proteins were expressed in *Escherichia coli* (*E. coli*) host systems and were sold for R125–215/µg [99,100]. The estimated price in this paper equated to R0.059–0.089/µg and was used in further calculations, as it was below the market price of lab-purity miraculin.

Alternatively, miraculin was considered as a substitute for sucrose and would need to be economically competitive to replace common sugar. Therefore, a miraculin price range was estimated by considering sucrose retail prices and the miraculin:sucrose molecular ratio required to induce a similar sweetness [56]. Table S18 elaborates on the calculations which resulted in a miraculin price range of R290,481–376,830/kg in Table S19.

The profitability of TM was evaluated further based on the sugar equivalent pricing. Table 13 shows the revenue potential when considering the miraculin pricing based on miracle berries, but it was assumed that the large-scale adoption of miraculin would not focus on lab-grade pricing. The miraculin pricing which was based on sugar equivalent value was a more realistic value for further evaluation. Based on published miraculin accumulation levels [74] and the required amount of miraculin to induce taste modification [56], the TM scenario yielded favourable ROI values in Figure 6. It resulted in a 99.9% probability of making a profit and an 87% probability of making a ROI larger than 20%.

The sensitivity analysis in Figure 7 shows that the ROI was primarily dependent on miraculin accumulation levels in the transgenic tomatoes. This also explained why planting density and fresh mass per tomato plant were significant. The top three variables all related back to the annual miraculin being produced in TM, and as miraculin was the primary product of the TM scenario, it had the most significant influence on profitability.

The annual capital for uncertainty, R3,031,137–R19,655,509 must consider market demands and absorb downstream processing costs to obtain miraculin in a usable form. This includes extraction and purification costs [101,102] and variable recovery rates of 45–62% [74] from transgenic tomatoes. Depending on the application, miraculin extraction and purification from host plants is not needed [57]. Miraculin has also been shown to accumulate in successive generations of transgenic tomatoes, which meant that plant transformation was not required at the start of each crop cycle [74] Lastly, miraculin is mostly accepted and researched in Japan [57,74] and requires more widespread acceptance before it can reach large-scale market penetration.

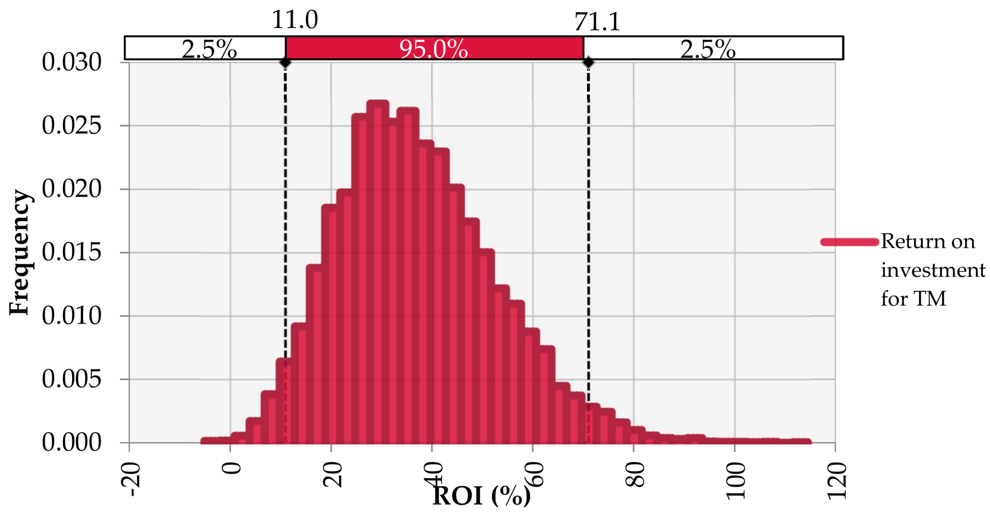

Figure 6. Probability density distribution of the return on investment (ROI) for the tomato–miraculin (TM) scenario based on sugar equivalent pricing.

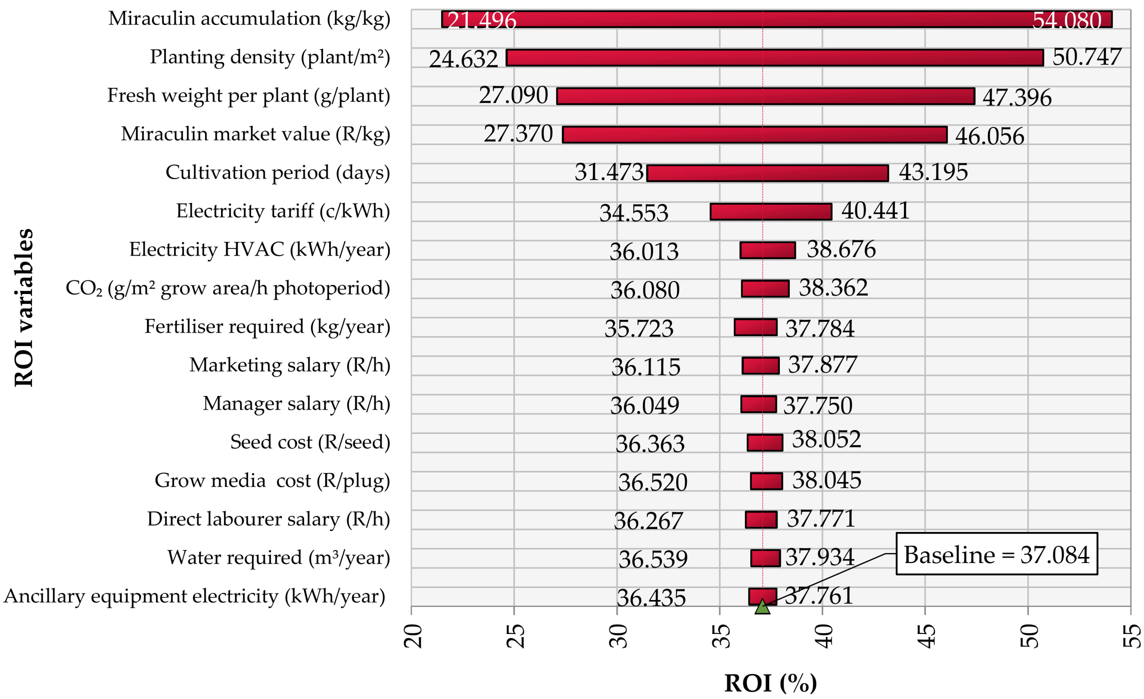

Figure 7. The sensitivity of return on investment (ROI) for the tomato–miraculin (TM) plant factory scenario.

4.4.2. Lettuce-Based Plant Factory Revenue Results

The main economic indexes for the lettuce scenarios are shown in Table 13 by using the market values and product yields from Table S20. The baseline LF scenario showed promising revenue potential by selling edible lettuce directly to the consumers. As with TF, the producer price did not provide a pathway towards profitability. The need for asking a premium price for hydroponic and pesticide-free lettuce was confirmed by the cultivation cost of R40–101/kg for lettuce. An average ROI of 31% was achieved with a payback period of 3.23 years. The LF scenario showed a 99% probability of making a profit in Figure S10 and a 72% probability of making a ROI of 20% or more. The ROI value was mostly influenced by lettuce mass per plant, planting density, and cultivation time in Figure S11. The LM scenario achieved an average ROI of −29%. This was attributed to the low accumulation levels of miraculin in lettuce [75], and excluded LM from further analysis.

Lastly, the individual and combined contributions of PV panels and brewers' spent grains were marginal when considering the average ROI value of LRI to the baseline LF scenario. The ROI reduced from 31% to 29% when only considering the influence of rooftop PV panel installations. This reduction was attributed to the increased CAPEX cost and yearly depreciation of the panels in Table 7. Additionally, the plant factory dependence on grid electricity was only reduced by ~10% without expanding the plant factory footprint to allow for additional renewable energy to be generated. Zeidler, Schubert, and Vrakking [7] also concluded that the high energy requirements of plant factories limited the economic impact of façade-based PV panel installations. The energy generated from the PV system was also subject to variability, such as panel degradation, solar availability and policies regarding independent power generation.

The use of brewers' spent grains increased the baseline ROI from 31% to 33% but it was assumed that spent grains could fully substitute inert grow media, such as rockwool. In reality, the spent grains would need to be moulded or placed in containers to function as hydroponic grow media. This would have to be absorbed by the capital buffer provided using spent grains. Despite the marginal economic benefits shown in Table 13, the use of spent grains is an act of waste valorisation and carries environmental benefits with its use [16], although these benefits were not discussed in this paper.

4.4.3. Tobacco-Based Plant Factory Revenue Results

The revenue potential of TPHB was calculated by only considering the value of accumulated PHB polymers in the transgenic tobacco. The economic feasibility of TPHB was evaluated by using published prices for PHB [103] and by considering PHB to be equal in value to polypropylene, as they shared similar properties [76]. The revenue potential of TT and TTD was linked directly to the accumulation of HBV antibodies and their market price. The market data in Table S21 was used, along with the CAPEX and OPEX results of the tobacco scenarios, to calculate the economic indexes in Table 13.

The TC and TPHB scenarios were omitted from further analysis after the potential revenue and cost of cultivation values were calculated. The TC maximum revenue potential of R3,329,928 per year was obtained by selling tobacco plants for the producer price. The scenario of selling the tobacco for the simultaneous production of methane, biodiesel, and artemisinin extraction resulted in a maximum potential revenue of R163,019 per year and was significantly lower than the annual cultivation costs of R8,743,519–R10,795,692. Yang et al. [51] investigated the accumulation of artemisinin and PHB in biomass feedstocks to supplement biofuel production costs but required the feedstock to cost ~R1.40/kg, instead of the calculated R147–203/kg.

The TT and TTD scenarios were similar in nature as both cultivated transgenic tobacco plants expressed HBV antibodies. The variations in revenue potential and cultivation costs were fully attributed to the genetically modified tobacco plants in TTD that resulted in dwarf plants. This allowed for more plants to be cultivated in the same growing area and did not influence HBV antibody expression [62]. The elevated annual revenue potential in TTD from R25,231,351–R48,806,539 to R27,519,590–R51,613,595 served as an example of how the genetic modification of crops could be used in plant factory infrastructure to improve profitability and limit the exposure of genetically modified crops to the environment [43]. The economic indexes of TTD were discussed further, as it was the most profitable tobacco-based scenario. The economic potential of TTD is illustrated by Figure 8, which shows a 95% probability of achieving a ROI between 61–148% and which resulted in an average payback time of one year. This also resulted in an annual capital buffer of R16,888,055–R41,009,508 to mitigate against uncertainty and generate a profit. For TTD, the excluded costs included successful transformation of tobacco plants to induce a dwarfing effect and to express HBV antibodies at the specified levels [62], the extraction and purification of HBV antibodies from the transgenic host plants, navigating regulatory frameworks for plant-made pharmaceuticals [43,104,105], and the market demand of plant-made pharmaceuticals.

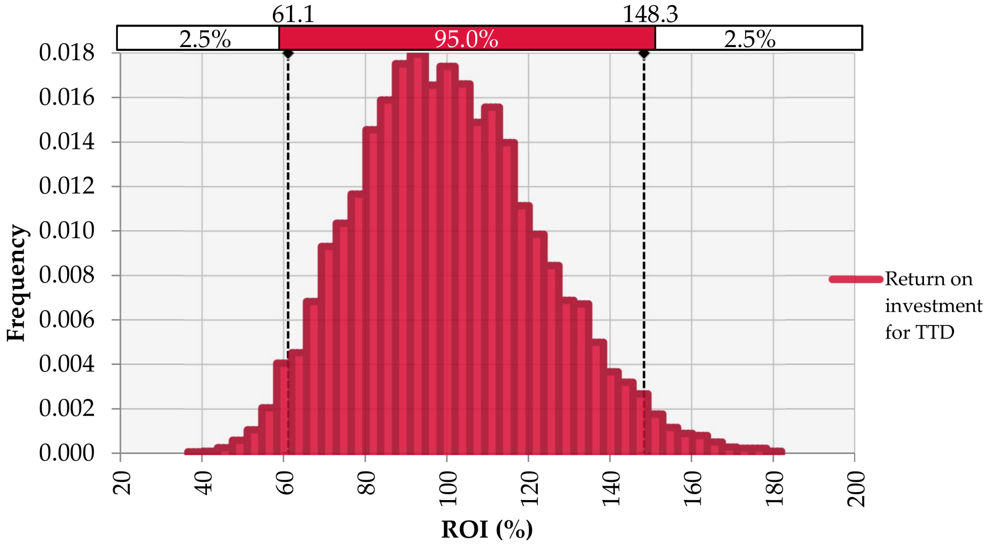

Figure 8. Return on investment (ROI) for the tobacco–transgenic–dwarf (TTD) scenario.

Figure 9 shows that the profitability of TTD was most dependent on the level of HBV antibody expression in the host plant, and was followed by the planting density in the plant factory. This highlighted the importance of research into improving the expression levels of value-added compounds in transgenic host plants. The sensitivity of the planting density also drew attention to the impact which the tobacco dwarfing had on TTD profitability.

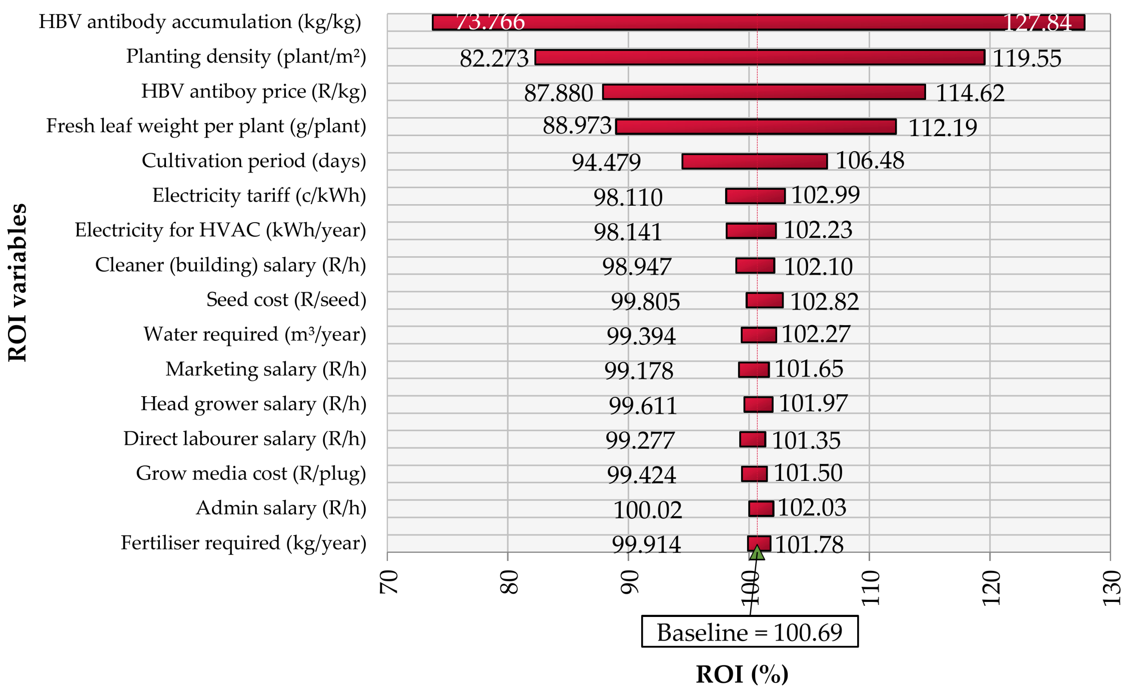

Figure 9. The sensitivity of return on investment (ROI) for the tobacco–transgenic–dwarf (TTD) plant factory scenario.

The novelty of producing plant-made pharmaceuticals on a large scale added another layer of uncertainty to TTD and made it a high-risk and capital-intensive scenario. In an attempt to mitigate against some of the mentioned uncertainty, TTD was also evaluated to determine how much of the 2720 m^2 growing space had to be dedicated to the cultivation of dwarf tobacco plants which expressed HBV antibodies to obtain an average ROI of 20%. This evaluation concluded that ~41%, or 1102 m^2, of the total 2720 m^2 had to be dedicated to the cultivation of the transgenic tobacco plants to obtain the desired ROI. The remaining 59% of growing area could be used to cultivate biomass that required fewer environmental control and resource inputs. This result suggested that plant factories could make use of a multiple revenue stream approach to mitigate against the uncertainty of market demands for specialty products.

4.4.4. Cannabis-Based Plant Factory Revenue Results

As shown in Table S22, the economic indexes, in Table 13, were calculated using the leaf and inflorescence yields in CC. Despite only selling ~30 wt% of the total cannabis biomass, a favourable average ROI of 508% was achieved and resulted in a payback period of 0.20 years. The probability density distribution is shown in Figure S12. The cultivation costs of R455–1,480/kg cannabis plants and R1,516–4,935/kg of cannabis leaves and inflorescences also reflected the high seed costs.

The ROI was also mostly influenced by cannabis fresh weight yields, planting density, and market prices, as shown in Figure 10. The financial impact of cannabis yields and planting densities further motivated the use of plant factory infrastructure. Research into plant factory design and optimised environmental control can directly influence biomass yields and increase planting densities to increase the profitability of CC even further.

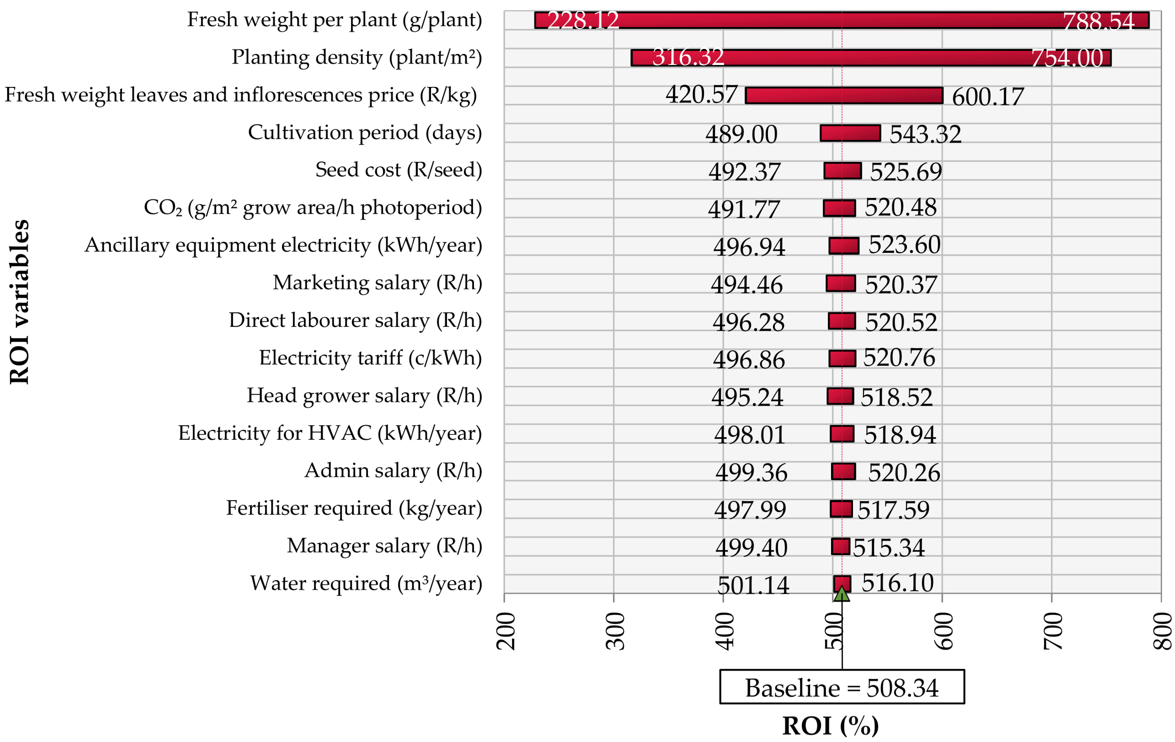

Figure 10. The sensitivity of return on investment (ROI) for the cannabis–conventional (CC) plant factory scenario.

As cannabis biomass was typically sold directly to the end-user market, there were not many downstream processing steps which had to be mitigated with the annual R31,597,483–R199,523,749 capital buffer. Uncertainties included more conventional cultivation issues, such as drying, storage [106], yield variability, and harvest loss through contamination. Uncertainties more specific to cannabis cultivation included country-specific legislation regarding allowable levels of psychoactive tetrahydrocannabinol (THC) for the legal cultivation of cannabis. Research into the medicinal value of secondary metabolites in cannabis was still ongoing and limited its marketability [67,93]. Therefore, the profitability of CC was significantly dependent on local perception towards cannabis cultivation and government legislation concerning its cultivation.

5. Discussion

This section elaborates on the economic feasibility of the plant factory scenarios which were evaluated. The results of the plant factory scenarios were discussed in terms of the crop and product selection for each of the scenarios to highlight the economic impact which these variables had on the plant factory business case.

5.1. Tomato-Based Plant Factory Scenarios

The tomato-based plant factory scenarios both showed economic feasibility, with TF achieving an average ROI of 11% and TM an average ROI of at least 37% in Table 13. The profitability of TF was conditional on selling edible tomatoes directly to consumers at a premium price, while TM had to sell miraculin at an appropriate price to be competitive against sugar alternatives. Although TM had higher revenues and a more favourable payback period than TF, it also carried more risk and uncertainty. The food market of TF was more developed than the biopharmaceutical/bio-based product market which TM had to enter. The successful accumulation of miraculin was also still a topic of research [107] and brought along marketability issues due to the lesser-known nature of miraculin. This was also seen in LM, which was unable to accumulate miraculin in sufficient quantities using lettuce as a host plant [75].

5.2. Lettuce-Based Plant Factory Scenarios

The baseline food market lettuce scenario, LF, showed an average ROI of 31% when it was able to ask its hydroponic food premium price. The need for a high retail price was illustrated with the R40–101/kg lettuce cultivation cost in Table 13. Comparison with LF showed that the installed PV panels and brewers' spent grain as growth media in LRI had a marginal impact on the economic indexes. Despite this, an argument can still be made for greater self-sufficiency when it comes to the power demands of plant factories. The risk mitigation of independent power generation was not reflected in the economic indexes. Similarly, the larger economic impact and environmental benefits of valorising spent grains can also extend beyond the plant factory.

5.3. Tobacco and Cannabis Plant Factory Scenarios

The low revenue potential of TC and TPHB illustrated the importance of selecting appropriate crops and value-added compounds for plant factory cultivation. Although tobacco was one of the few crops which were able to accumulate artemisinin [59], the accumulation levels and market value of the anti-malarial drug did not motivate the use of a plant factory for its accumulation in TC. Similarly, the accumulation of PHB in TPHB also did not reach profitability when considering the R9,325,878–R11,383,441 annual cost of cultivation within the plant factory. The potential of using tobacco as a host plant was reaffirmed in TT and TTD which accumulated HBV antibodies and achieved ROIs of 93% and 101%, respectively, and showed the economic potential of leveraging the environmental control in plant factory infrastructure within the biopharmaceutical industry. The TTD scenario also showed increased revenues, compared to TT, due to the dwarfing of the tobacco plants in the plant factory. Lastly, the cannabis cultivation in CC resulted in an average ROI of 508%. Despite this value, the economic viability of cannabis cultivation remains dependent on country-specific legislation which could prohibit the market from expanding. The value of cannabis plants was also reflected in its elevated cultivation costs of

R16,702,559–R28,286,586 per year, which meant that harvest losses through contamination or legislation would result in significant financial losses for the plant factory.

5.4. Economic Feasibility of Plant Factory Scenarios

The economic modelling of the developed plant factory scenarios in this paper illustrated the economic feasibility of plant factories, within the constraints and limitations of this paper. The plant factory scenarios showed that the largest cost driver was electricity demand, which was primarily associated with artificial lighting requirements. This result is similar to the existing plant factory modelling literature [8,14] and the novel plant factory scenarios in this paper were unable to change this cost constraint. Scenario LRI investigated the use of PV panels to reduce electricity demand, but it was concluded that the cost mitigation remained marginal if the plant factory footprint was not expanded to facilitate additional energy generation [7]. Alternatively, a smaller cost driver, fertiliser demand, was reduced significantly in LRI by substituting industrial by-products as fertiliser material [16,21,80]. This illustrates the economic benefit of reducing plant factory expenses where possible, even if it is not the main cost driver.

The effectiveness of the economic model in this paper was evaluated using Scenario TF and Scenario LF, which cultivated edible tomatoes and lettuce, respectively. Edible biomass has shown profitability in the existing literature of plant factories [7,8]. These scenarios also had the least amount of uncertainty associated with the economic model results as the omitted costs primarily included packaging, storage, and transportation of the biomass to markets. The remaining plant factory scenarios had higher levels of uncertainty, as the end-user markets were not the food market.

Scenario TM and Scenario LM both accumulated miraculin as the value-added compound to be sold in the biopharmaceutical market. The economic indexes for Scenario LM were not favourable, and this was attributed to the low levels of miraculin accumulation [75]. The miraculin accumulation in tomatoes was significantly higher [74] and resulted in favourable economic indexes for Scenario TM. This highlights the importance of selecting appropriate host plants when accumulating value-added compounds within plant factories. Despite the results of Scenario TM, certain limitations still apply. The economic model did not consider the costs of transforming the host plants to allow miraculin accumulation. Furthermore, downstream extraction and purification efficiencies were not included in the economic modelling [101,102]. The reported capital for uncertainty must account for these omissions, and future studies can include the upstream and downstream considerations to provide a more comprehensive assessment of the economic feasibility of accumulating miraculin in transgenic host plants within plant factories. At the time of writing this paper, miraculin accumulation was still being researched [107] and has not reached large scale market adoption. This contributes to the economic uncertainty of Scenario TM.

The tobacco-based scenarios were assessed due to the reported effectiveness of using tobacco as a multipurpose crop and host plant for the accumulation of value-added products [51,59–65,77]. Scenario TC and Scenario TPHB were found to be uneconomical within a plant factory environment. Scenario TC was modelled using tobacco market values [108], biofuel conversion yields [63,65,77], and reported artemisinin accumulation levels [59]. Despite the variety of potential products which were evaluated, Scenario TC did not reach profitability. This was attributed to the insufficient accumulation levels of value-added compounds and low biofuel prices [94]. Furthermore, downstream considerations also limited the economic feasibility of cultivating biofuel feedstocks in plant factories. Taking biomethane production as an example, it was found that large-scale biomethane production facilities were most profitable [4]. This would require plant factories to have large cultivation capacities and to be located close to biomethane facilities to improve the economic feasibility of supplying biomethane feedstocks through plant factories. The profitability of biomethane production facilities also improves when using waste streams as feedstocks, although this requires adequate amounts of feedstocks to be sourced from industries which generate the required feedstocks as waste material [4]. This also means that plant factories will not be economically viable while producing biomethane feedstocks as primary products. As with many biofuel conversion processes, value-added compounds are required to improve the economic feasibility of biofuel production [51]. In the case of this paper, no profitable plant factory scenario was found which simultaneously produced biofuel feedstocks and value-added compounds. The low profitability of biofuel conversion could not motivate the use of plant factory infrastructure to cultivate biomass feedstocks.

Similarly, Scenario TPHB did not reach profitability, although the accumulation levels of PHB in transgenic tobacco plants was second only to Arabidopsis [109]. Despite the larger size of tobacco plants and the reported accumulation levels [60,110], profitability was not achieved in Scenario TPHB. This was especially true when considering PHB pricing to be equivalent to polypropylene prices [111]. This was relevant, as PHB shares properties similar to polypropylene and can be considered as an alternative product [76]. The bacterial fermentation process of obtaining PHB has also been evaluated previously by the application of LCA to estimate the environmental impact of producing the biopolymer [112]. From the assessment, it was concluded that PHB production had a significant environmental impact. This was attributed to the low PHB yields which were obtained through bacterial fermentation, and the significant amount of raw material which was needed for the process [112]. The LCA found that an improved PHB yield would have the most beneficial impact on the environmental assessment, as this would reduce feedstock demands for PHB production. The research concluded that the PHB biopolymer required improved production processes to become economically viable. Despite the reported need for an improved PHB production method, the PHB accumulation levels in the transgenic tobacco host plants in this paper were insufficient to allow Scenario TPHB to reach profitability in plant factories. This indicates that additional work will be required to improve PHB production levels, whether the method is bacterial fermentation or transgenic accumulation in host plants.

The effectiveness of using tobacco as a host plant was demonstrated in Scenario TT and Scenario TTD. Both scenarios showed economic feasibility in plant factories by accumulating HBV antibodies at reported levels [62]. Scenario TTD also demonstrated the robustness of tobacco as a host plant by illustrating the improved economic indexes, relative to Scenario TT, after the tobacco plants were dwarfed. The dwarfing allowed more tobacco to be cultivated in the same growing space and did not influence the HBV antibody accumulation levels [62]. Scenario TTD demonstrates the economic benefit of identifying an appropriate plant factory crop and pairing it with high-value products. The profitability of Scenario TTD must still be considered in the context of omitted expenses and economic model assumptions. The costs associated with the host plant transformation were not included in the economic model. This included the dwarfing and transformation which allowed for HBV antibody accumulation in the host plants. Furthermore, downstream extraction and purification costs were also not included. The authors are aware that these costs must be considered in future research, and that the profitability of Scenario TT and Scenario TTD would decrease because of it.

Lastly, Scenario CC showed the highest return on investment of all the developed plant factory scenarios. This was attributed to the high-value nature of cannabis seeds and plants [96,113,114]. The economic feasibility of Scenario CC is dependent on country-specific regulations and legislation regarding the cultivation and consumption of cannabis. The legality of cannabis varies significantly between countries and limits the market potential of Scenario CC, but an investigation into country-specific legislation regarding cannabis cultivation was beyond the scope of this paper.

The authors are aware that comments made regarding the economic feasibility of plant factory scenarios, which extend beyond the food market, are in the context and within the limitations of the economic model in this paper. The most significant limitations are the omission of upstream and downstream processing steps, which will influence the final economic indexes of plant factory scenarios. These omissions are considered as work for future research into the economic modelling of plant factory scenarios.

5.5. Implications and Limitations

This paper was used to explore plant factory scenarios which produced crops and value-added compounds for multiple markets within the biorefining industry. These scenarios were evaluated for economic feasibility and provided a range of crops and value-added compounds which showed favourable economic conditions through cultivation within the plant factory system, particularly when considering the TM, TT, and TTD scenarios, which accumulated biopharmaceutical products within plants grown in the plant factories. This paper explored crop and product selections for plant factories which have not been evaluated previously for economic feasibility and, as such, contributes towards the body of knowledge for expanding the market potential of plant factories.

As this paper is aimed at expanding the range of applications of plant factory structures, it required some novel approaches to be taken in terms of defining the plant factory system boundary and exploring its applications beyond that of food production. Some of the most significant scientific contributions to the existing body of knowledge included the following:

- Exploring how the plant factory system boundary can be conceptualised to show dependencies within the greater economy;
- Contributing to the debate around the use of plant factories by providing a new perspective to the applicability of the plant factory concept within the greater biorefining industry.

The practical contributions, for practitioners of plant factory cultivation, are a novel plant factory system boundary which can be used in the assessment of new or existing plant factory projects and an expansion of the crop and product selection process for plant factories which considers crop value in terms of value-added compound accumulation levels and pricing in markets other than the food market. It is envisioned that the combination of scientific and practical contributions can be used to help in the design and implementation of plant factory projects of practitioners that wish to expand beyond the food market.

Throughout this research, several deficiencies were found in the literature and due to the constraints of this paper. These deficiencies and constraints are listed and presented as recommendations for future research:

- The initial review of the plant factory literature in Section 2 alluded to the fact that crop yield data were not easily available for crops grown in plant factories. Directly comparable results of crop yields and cultivation conditions under varying degrees of CEA were even more scarce. This paper had to use best-available crop data to populate the economic model, which approximated the crop growth rates under specific cultivation conditions. Future research can include the standardised cultivation of various crops to draw a clear correlation between crop growth performance and the level of environmental control provided by CEA structures.
- The economic feasibility analysis of this paper considered the costs associated with operating plant factories within the defined scenarios. The revenue potential of these scenarios was based on the revenue potential of the final products which would be produced within the cultivated biomass in each plant factory. This paper calculated capital for uncertainty to put the economic indexes of each scenario in the context of the omitted expenses of the economic model. Future research can include the expansion of the economic feasibility analysis to include the downstream processing steps which were omitted from the analysis. This will lead to a more detailed techno-economic analysis which includes the extraction and purification costs of value-added compounds from host plants.
- The economic feasibility analysis also only considered monocultures within a specific scenario. Future research can include the investigation of contract farming within plant factories and the simultaneous cultivation of different crops to produce a variety of products for multiple markets.

6. Conclusions

This paper was explorative in nature while aiming to expand the economic potential of plant factories beyond the food market. Novel plant factory scenarios with crop and value-added product combinations were investigated for economic feasibility. The novel scenarios required a plant factory system boundary which was able to describe the scenarios and an economic model which was able to illustrate the economic potential of the proposed plant factory markets. The appropriateness of the plant factory system boundary and economic model which were used in this paper was illustrated by showing economic feasibility of well-defined plant factory scenarios which serviced the food market.

Based on the scenarios which were investigated, multiple combinations of crops and value-added compounds showed favourable economic conditions in plant factories, and it was concluded that the biopharmaceutical industry was well positioned to leverage the environmental control and insulation of plant factories to produce high-value biopharmaceutical products. This paper contributed towards the body of knowledge of plant factories by exploring its application to markets within the biorefining industry. This was achieved by identifying and proposing novel plant factory scenarios and by evaluating the economic feasibility of plant factories within markets other than the food market. At the time of writing this paper, the majority of the economic literature related to plant factories was in the context of producing edible biomass for the food market.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15021324/s1. Additional information can be found in the Supplementary Materials document, and includes ancillary information, such as the assumptions and technical specification which were used to perform the economic feasibility analyses. This information is shown in Table S1: Plant factory design and operational considerations; Table S2: Supply chain considerations as part of a plant factory system boundary; Table S3: Biorefining market considerations for plant factory projects; Table S4: Economic model assumptions; Table S5: General information used in the plant factory model; Table S6: The plant factory footprint (1000 m^2) components equated to typical structure construction costs in South Africa; Table S7: Plant factory cost estimates and calculated cost per grow level; Table S8: Fertigation system cost calculations; Table S9: Monitor and control cost calculations; Table S10: Salary and position breakdowns; Table S11: LED light system specifications and electricity use; Table S12: Electricity pricing structure; Table S13: HVAC calculations for plant factory scenarios; Table S14: Water consumption and fertiliser data for plant factory scenarios; Table S15: Growth media and seed demand for plant factory scenarios; Table S16: CO_2 supplement for plant factory scenarios; Table S17: Plant factory dimension descriptions for each scenario; Table S18: Miraculin cost estimates based on miracle berry prices and sucrose equivalency; Table S19: Tomato-based plant factory yields and market values; Table S20: Lettuce-based plant factory yields and market values; Table S21: Tobacco-based plant factory yields and market values; Table S22: Cannabis-based plant factory yields and market values; Figure S1: The sensitivity of cost of goods sold (COGS) values for the tomato—food (TF) plant factory scenario; Figure S2: The sensitivity of cost of goods sold (COGS) values for the tomato—miraculin (TM) plant factory scenario; 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; Figure S10: Probability density distribution of the return on investment (ROI) for the 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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