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Exploring the Industrial Symbiosis Potential of Plant Factories during the Initial Establishment Phase

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Abstract: Plant factories can be described as structures that facilitate the indoor cultivation of crops and are typically considered to be closed-loop (isolated) systems which are situated within the urban environment. This paper explores the extent to which external industries can be integrated with plant factories by defining an open-loop (integrated) plant factory system boundary. A multi-criteria decision-support process was developed and included the use of a mixed-indicator assessment method and the use of fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to account for the uncertainty associated with indicator-based assessment methods. The assessment of theoretical industrial symbiosis scenarios showed that the fuzzy TOPSIS ranking provided a clearer hierarchy of optimal scenarios, when compared to using the indicator rankings. The novelty of the paper included the clear illustration of the points of integration between plant factories and external industries, which can be used to identify alternative integration scenarios in the future. Furthermore, this paper provided detailed descriptions and motivations of the indicator scoring of theoretical industrial symbiosis scenarios so that the early phase assessment method can be used beyond the scope of this paper and can be expanded with more well-defined indicators in the future.

Keywords: urban agriculture; plant factory; industrial symbiosis; multi-criteria; decision-making; mixed indicators

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1. Introduction

Plant factories can be considered as technologically advanced structures that allow for urban agriculture by cultivating crops indoors [1]. Crop production in plant factories can be regarded as a supplement to open-field cultivation [2] that can provide fresh produce to urban dwellers [3,4]. The technological and economic feasibility of plant factories is often evaluated through the review of applicable plant factory technologies [5,6] and the associated increase in biomass yields resulting from technology interventions in the plant factory [7]. The literature regarding the economic analyses of plant factories has indicated that the main cost drivers included lighting, air management, land, infrastructure investment and labour [8–10]. Previous studies reviewed technology solutions that could mitigate these costs, such as renewable energy [11], automated harvesting [12], improved nutrient delivery systems [6,7] and Internet of Things (IoT) management systems for improved resource use efficiencies [13]. With a closed-loop (isolated) system boundary assumed for plant factories, the costs and benefits of selected technologies are significant when considering the economic feasibility of a plant factory. An alternative approach is to consider the plant factory as an open-loop (integrated) system which can be integrated with surrounding processes and industries to improve resource use efficiency, reduce operating costs and promote industrial development near plant factories. This paper is concerned with the concept of industrial symbiosis and its application to plant factories.

1.1. Contextual Background

Thomson et al. [14] argued that a plant factory is not truly an isolated closed-loop system. Zeidler, Schubert and Vrakking [10] concluded in their economic evaluation that plant factory integration with external industries should be investigated further to assess the potential economic benefits and that plant factory integration should be considered in the future for new industrial cluster developments. Scott, Rutzke and Albright [15] considered industry integration at the greenhouse level of controlled environment agriculture and, more recently, the environmental impacts of integrating urban vertical farms with external industries were investigated [16,17]. Previous studies have considered the integration of plant factories with specific external industries and processes, such as aquaculture systems [5,18], heat energy recovery systems [10,19], multipurpose land use [3,20–22] and CO_2 recovery systems [10,14,18,23], to name a few. Despite these types of individual integration studies, plant factories are still not widely considered as nucleating agents for industrial symbiosis.

Industrial symbiosis is a concept that considers the ways in which separate entities, such as companies, can cooperate with one another for improved economic, environmental and social gains [24]. The ways in which separate entities can integrate and the way in which the integration scenarios are assessed make up the field of industrial symbiosis research. The review by Neves et al. [24] identified the industries that typically take part in industrial symbiosis initiatives, with manufacturing, water treatment, energy and agricultural processes being the most common. Neves et al. [24] also considered the methods of evaluating industrial symbiosis configurations and found that the methods varied as widely as the stated objectives of the assessments. Industrial symbiosis assessment methods included the quantification of economic, environmental and social impacts (triple bottom line), barriers to entry of industrial symbiosis and the overall stability of intended industrial symbiosis networks. The triple bottom line (TBL) method also found favour in sustainability assessments [25].

Walker et al. [26] reviewed sustainability assessment methods for circular economy network design, which can be considered as part of industrial symbiosis design. The review summarised typical evaluation and decision-support methods for assessing circular economy practices and the sustainability performance of processes and networks. Typical evaluation methods included life cycle thinking [27], input-output analyses, indicator assessments and indices. Decision-support methods, which were typically used in combination with the mentioned evaluation methods, included heuristics, mathematical programming, multi-criteria decision-making, simulations and analytical models [26]. A well-defined industrial symbiosis assessment method is the combined use of indicators and a multi-criteria decision-making system [26]. An indicator-based evaluation method allows for qualitative- [28], quantitative- [29] and mixed-indicators [30] to be used to define and describe industrial symbiosis scenarios. The multi-criteria decision-making component also allows for the selection of an appropriate method, which can help the decision-maker select an industrial symbiosis scenario from a selection of options.

Decision-making methods can include Analytical Network Process (ANP), which expresses the relationship between criteria [31], Analytical Hierarchy Process (AHP), which requires stakeholders to define the relative importance of decision criteria [32], fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy TOPSIS), which provides rankings of scenarios based on the distance from the ideal solution [33] and VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), which provides compromise solutions based on which solutions are closest to ideal [33,34], to mention a few options [26]. Multi-criteria decision-making has also found widespread application, with AHP being used for risk assessment [35], TOPSIS being used for biomass selection [36], fuzzy TOPSIS being used for supplier selection and recycling planning [33,37], combined AHP-TOPSIS also being used for risk assessments [32] and ANP being used to evaluate industrial symbiosis sustainability criteria [31]. Similarly, the multi-criteria decision-making literature also includes comparative analyses of methods to highlight the differences of results when using specific decision-making methods [34,37].

For this paper, only TOPSIS was considered due to its popularity as a simplistic method, which is easily computed with minimal inputs from stakeholder. The disadvantage of TOPSIS is that its simplicity does not allow for the effective processing of subjective stakeholder inputs. Therefore, only fuzzy TOPSIS is considered further, as the fuzzy logic concept allows for vague or ambiguous user-inputs to be processed [33]. A more comprehensive review of multi-criteria decision-making methods was beyond the scope of this paper and is recognised as an opportunity for further research.

1.2. Knowledge Gap in the Literature

A research opportunity was identified in this paper to combine the research concepts of plant factories and industrial symbiosis using a multi-criteria decision-support system. By developing an industrial symbiosis assessment method for plant factories, this paper expands on the field of knowledge regarding the establishment of plant factories and incorporates the concept of plant factories into the established industrial symbiosis literature. This paper investigates the use of an open-loop system boundary approach to identify points of integration between a typical plant factory and surrounding industries. A method is proposed to evaluate the integration of plant factories with these potential industries and processes. This method is used as an early phase assessment in the absence of sufficient quantitative data to aid in the site selection of plant factories, based on the availability of specific industries in an area, or to consider the industrial development potential, which can follow the establishment of a plant factory with its associated points of integration.

1.3. Research Aim and Structure

The aim of this paper is to explore the extent to which external industries can be integrated with plant factory projects to improve the economic viability of plant factory business case scenarios and reduce the operating costs while producing biomass. This is achieved by using established plant factory literature and industrial symbiosis knowledge to identify industrial integration opportunities for plant factories. Integration opportunities are assessed using the developed assessment method in this paper, and the significance of the identified integration opportunities is discussed in more detail for what it can mean for new and existing plant factories.

Section 2 elaborates on the methodology which was used to define an open-loop plant factory system boundary which indicates the potential points of integration with external industries. The theoretical integration case studies are presented, and the development and use of the plant factory industrial integration assessment method is explained. Section 3 provides the descriptions of theoretical plant factory integration scenarios which are identified using the open-loop plant factory system boundary approach. The theoretical industrial symbiosis scenarios are assessed with the developed assessment method and the indicator and fuzzy TOPSIS rankings of the assessment method are reported. Section 4 discusses the integration potential of the theoretical scenarios based on existing literature of similar industrial symbiosis case studies, reports on the novelty of the paper and highlights the limitations of the research and potential for future research. Section 5 concludes the paper.

2. Methodology

This section describes how an open-loop plant factory system boundary was defined and how points of integration between plant factories and external industries were identified using the system boundary. Furthermore, Figure 1 illustrates the methodology which was used in this paper to develop a multi-criteria, mixed indicator assessment method for the early phase evaluation of industrial integration potential of various industrial processes with plant factory initiatives, based on the open-loop system boundary approach and identified points of integration.

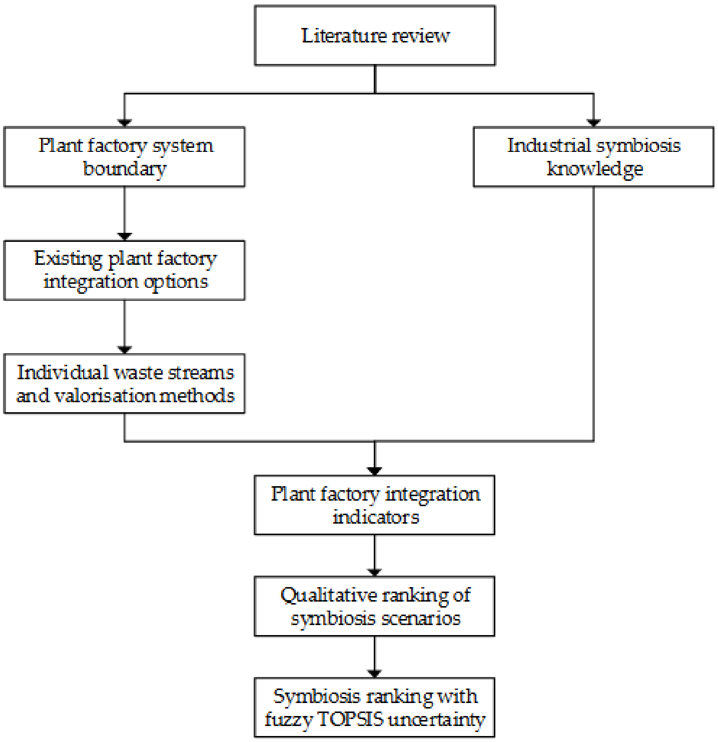

Figure 1. Methodology used for developing a multi-criteria, mixed indicator assessment method to assess the integration potential of external industries with plant factories.

Firstly, a typical plant factory system boundary was defined to identify input and output streams to the system, which could act as points of integration with external industries. Secondly, a review of industrial symbiosis literature was conducted to motivate and select an appropriate assessment method for evaluating plant factory integration scenarios. Lastly, integration indicators were derived from the established plant factory system boundary and a review of previously investigated controlled environment agriculture (CEA) case studies with varying degrees of external industry integration. The derived indicators were used to assess a selection of integration scenarios to illustrate the functioning of the industrial integration assessment method. Multi-criteria decision-making was incorporated into the assessment method to compensate for the uncertainty associated with the ranking of industry integration scenarios based on an aggregate indicator score.

2.1. Plant Factory System Boundary for the Identification of Points of Integration

This section defines a plant factory system boundary which accounts for the typical input and output streams to the system and uses these resource and waste streams as potential connection points to external industries and processes to guide the identification of industries to integrate with plant factories. The aim is to use the concepts of prevention, diversion, recovery and valorisation to improve resource use efficiency and the economic viability of plant factories [14].

Literature regarding the design and operation of plant factories was reviewed to identify the primary cost drivers during start-up and operation of the facilities. Table 1 summarises the main operating costs and yearly costs identified during the review.

The identified cost drivers were combined with the plant factory system boundary illustrated in Figure 2.

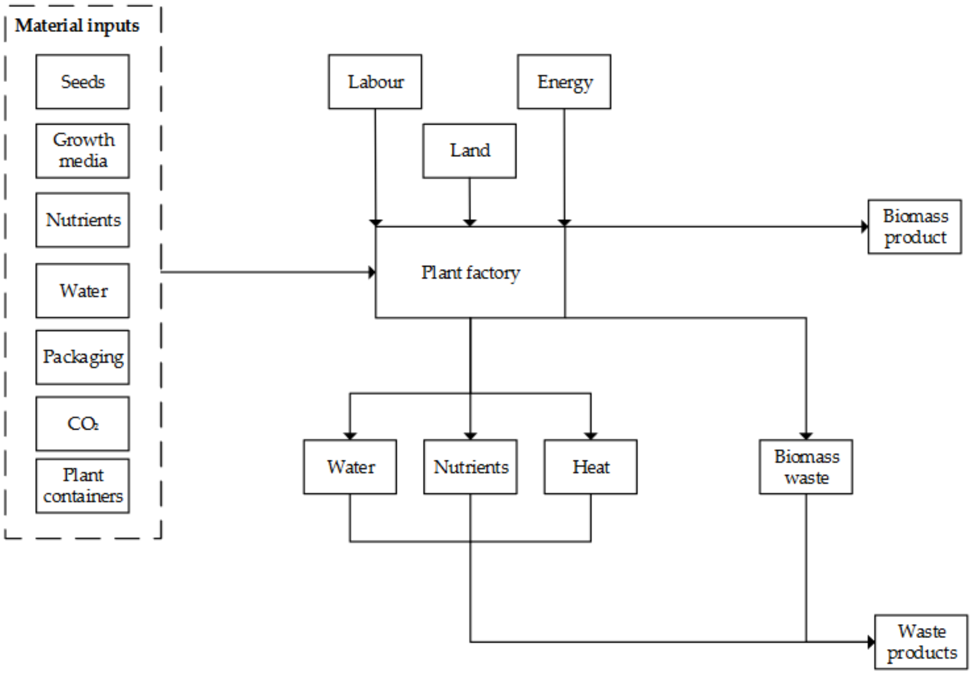

Figure 2. Adapted system boundary which highlights input and output streams from a typical plant factory.

Table 1. The operating expense (OPEX) breakdown of plant factories with artificial lighting assessed in the literature.

Resource Stream	Operating Cost % Breakdown		References
Energy consumption	28 21		[5] [9]
-Lighting	70–80 ~60 [a] 70 [b]		[38] [8] [10]
-Air management (heating, cooling, ventilation)	33 ~40 [a] 28 [b]		[39] [8] [10]
Depreciation	21		[9]
Labour	26 28		[5] [9]
Logistics (packaging and transport)	~10		[9]
Seeds and consumables	~10		[9]
Miscellaneous	~10		[9]
	Variable cost % breakdown [c]	Yearly cost % breakdown [d]	
CO_2	1	1	[10]
Electricity	~60	42	
Horticultural activities (fertiliser, seeds, plants)	20	15	
Investment (CAPEX payments)	-	28	
Labour	18	13	
Water	1	1	

[a] Values based on aggregated cooling values for plant factories in different regions. Values based on energy requirements per m^2 of floorspace. [b] Energy consumption simplified to illumination and air management (heating, cooling, ventilation) as it approximated 98% of total energy requirements in the vertical farm design. [c] Variable costs based on a modular vertical farm design that produces lettuce and vine tomatoes. [d] Yearly cost considers the capital expenditure (CAPEX) payments structured out over 30 years.

The open-loop plant factory system boundary shown in Figure 2 has a primary focus of indicating potential points of integration with external processes. The identified input- and output streams were similar to those found in previously developed plant factory system boundaries [17,40]. This system boundary was used to identify plant factory integration scenarios for further assessment.

2.2. Theoretical Plant Factory Integration Scenarios

A literature review was conducted to identify a selection of external industries and processes which had the potential to be integrated with plant factories. The identified points of integration in Figure 2 were used to guide the literature review and represented the synergistic potential between plant factories and external industries, as industrial symbiosis contributes towards the economic feasibility of plant factory initiatives [41]. It was beyond the scope of this paper to conduct a comprehensive review of all the processes which had the potential to be integrated with plant factories. Instead, the theoretical case study scenarios which were mentioned below were limited to those that could supplement the identified points of integration and which were previously discussed in terms of industrial integration in the literature. Table 2 summarises the theoretical case study scenarios which were assessed with the developed industrial symbiosis assessment method.

Table 2. Descriptions of integration scenarios that were assessed with the proposed industrial symbiosis evaluation method.

Integrated Plant Factory Scenario Designation	Industry/Process	Point of Integration	Integration Requirement	References
IPF1	Urban agriculture	Land	Urban planning and structural design	[3,20,42]
IPF2	Agrovoltaics	Land Energy	Spatial planning, design and energy capture infrastructure	[10,21,22]
IPF3	Aquaculture	Water Nutrients/Fertiliser	Piping, nutrient monitoring and supplementing systems, purification systems	[5,18,29,43]
IPF4	Beer brewery	Water Grow media Nutrients/Fertiliser	Nutrient monitoring and supplementing systems, product transportation	[1,16,44]
IPF5	Composting/ Digeponics	Nutrients/Fertiliser Grow media Heat energy CO_2	Aerobic, anaerobic digestion infrastructure, CO_2 capture, nutrient monitoring and supplementing systems, purification systems	[14,15,45,46]
IPF6	Coal-fired thermal power plant	Heat energy Water CO_2	Cooling water piping infrastructure, flue gas purification and separation systems	[23,47–49]
IPF7	Landfill	Heat (biogas) energy CO_2	Landfill gas stream separation technology and energy generation systems	[18,50]
IPF8	Biodiesel production	Water Nutrients/Fertiliser Biomass feedstock	Liquid fertiliser collection and sterilisation equipment and biomass transportation between the plant factory and biodiesel plant	[51]

The scenario selection process is described in more detail in Section 3 as the successful identification of integration scenarios forms part of the results of this paper. The theoretical scenario descriptions are high-level, as they were only defined by using the existing literature.

2.3. Developed Industrial Symbiosis Assessment Method

Based on the contextual background of Section 1.1 and the previously investigated environmental [27,52] and sustainability assessments [53] of plant factories, it was decided to make use of a mixed indicator evaluation method with a primary focus on qualitative indicators, as data acquisition was deemed to be difficult during early phase development of an industrial symbiosis network. This approach was similar to Kosmol et al. [54] and Rosa and Beloborodko [30], who used mixed indicators and quantitative indicators, which were easy to populate with minimal data. The scope of the assessment method in this paper was limited to only consider the integration benefits for the plant factory and by assuming adequate quantities were available in the identified waste streams to justify the integration assessment [16].

A variation of the TBL indicator set was used to define relevant indicators. The typical economic, environmental and social indicators were replaced with environmental, economic and network indicators [28,55] as the quantification of social indicators, such as those used in Global Reporting Initiative (GRI) G4 sustainability assessments, was better suited for the assessment of established companies or industries. Indicator-based assessments require inputs from industry stakeholders, experts or community participation for quantitative data population [56]. The industrial symbiosis assessment method in this paper made use of fuzzy TOPSIS as a multi-criteria decision-making method to compensate for the uncertainty associated with indicator-based evaluations, especially when qualitative indicators are used as in this paper.

2.3.1. Industrial Symbiosis Assessment Procedure

The methodology illustrated in Figure 1 shows how the industrial symbiosis assessment method was developed in this paper, using the existing knowledge of plant factories, industrial symbiosis and decision-making methods. Figure 3 illustrates the procedure for using the developed industrial symbiosis assessment method to evaluate plant factory industrial symbiosis scenarios.

The first step involves selecting a plant factory point of integration resource stream, which should be supplemented by an external industry. This is achieved using Figure 2, which highlights typical plant factory points of integration. This is followed by shortlisting viable industries, which can provide the resource found within the point of integration. Industry identification is achieved by consulting any source which is available to the user, whereas this paper relied on information derived from research articles that considered industrial integration of plant factories in the past. Once viable integration scenarios are identified, they are scored using the developed environmental, economic and network indicators in Section 2.3.2. The indicator scores provide a preliminary scenario ranking, which can be supplemented by applying fuzzy TOPSIS to the indicator scores. This is achieved by incorporating indicator weightings and a fuzzy logic scale to the indicator scores, as shown in Section 2.3.3. This accounts for some of the uncertainty associated with using the literature to score integration scenarios and provides some robustness to the integration scenario rankings.

2.3.2. Industrial Symbiosis Indicators

As mentioned earlier, a mixed indicator set was used in the form of qualitative environmental and economic indicators, along with a quantitative network indicator. Table 3 summarises the criteria associated with each of the indicator scores, while each of the three indicators were given a score range from one to five. A variation of the indicator scoring system by Rosa and Beloborodko [30] was used to describe the environmental and economic indicators. The environmental indicator included definitions for energy, water and material exchanges to accommodate different forms of waste stream integration. The indicator score definitions associated with the environmental impact on waste material valorisation was based on an European Union directive, which had a descending waste management hierarchy of waste prevention, reuse, recycling, recovery and disposal [57].

Table 3. Industrial symbiosis indicator score definitions.

Indicator Score	Measurement	1	2	3	4	5
Environmental impact	Energy	Expelling waste energy into the environment	Waste energy requires significant upgrading and integration infrastructure	Waste energy utilised as intermediate step to lower waste heat expulsion to the environment	Waste energy used with minimal infrastructure requirements and upgrading	Waste energy used efficiently with no upgrading requirements or heat expulsion to the environment
	Water	Water expelled into the environment, sewage system or sent to wastewater treatment	Water use for cleaning or rinsing	Energy recovered from wastewater	Energy and/or materials (nutrients) recovered from wastewater	Water recovered for use in primarily, large-scale, processes
	Material	Materials discarded through methods such as incineration and landfilling	Waste material used for a purpose which would have required virgin material	The recovery and reprocessing of waste material to serve its original purpose	The use as raw materials with minimal pretreatment requirements	Excess material from industries can be used directly without pretreatment or upgrading. Measures taken reduced waste quantity and limited adverse effects on humans and the environment
Economic impact	Profits and costs	Complex integration with low return on investment	Proposed integration does not provide a direct economic benefit. Limited to environmental, social or ideological benefits	Minimal economic feasibility. Restricted to minimal cost scenarios or subsidy requirements	Moderate economic benefit to industrial symbiosis	Significant economic benefits. Includes direct economic benefit from integration and economic potential unlocked through the proposed industrial symbiosis
Network connections	Number of connections	1	2	3	4	5+

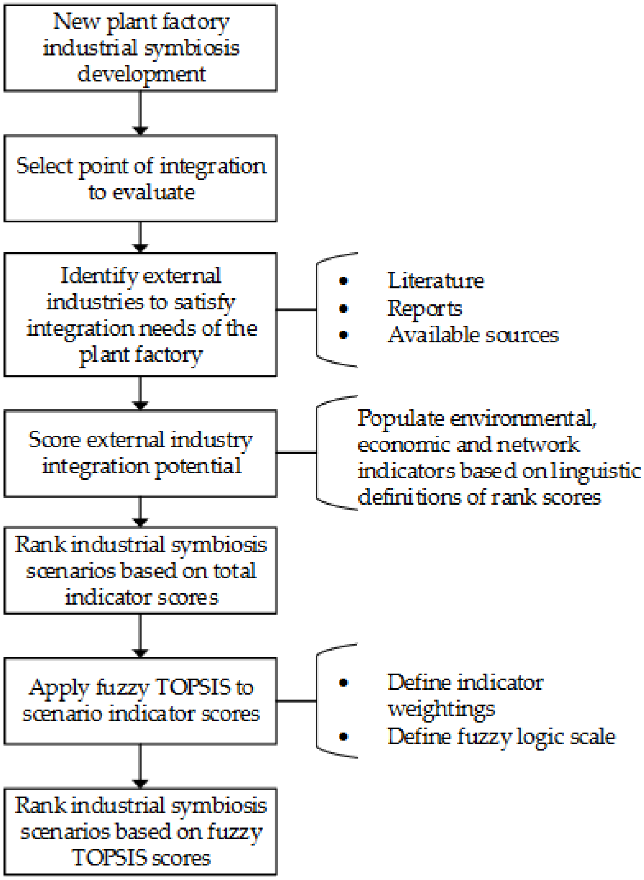

Figure 3. Procedure for using the developed industrial symbiosis assessment method for plant factory integration with external industries.

The quantitative network indicator was used to represent the number of points of integration that a specific external industry had in common with the theoretical plant factory. It was decided to not use more complex network indicators, as it would have required significant amounts of data acquisition to better describe the significance of the network connections. For the sake of simplicity, it was also assumed that the external industries did not interconnect and only integrated through the plant factory.

2.3.3. Fuzzy TOPSIS Calculations

Haddad et al. [33] and Khan and Ali [37] were consulted for the fuzzy TOPSIS procedure and equations. Table 4 shows how a quantitative five-point indicator scoring system can be equated to qualitative linguistic terms and a five-tier triangular fuzzy number scoring system.

Table 4. Triangular fuzzy numbers to be used to transform a quantitative five-point scoring system.

Environmental, Economic and Network Indicator Scores	Linguistic Variables	Fuzzy Numbers (a,b,c)
1	Very Low	(1,1,3)
2	Low	(1,3,5)
3	Medium	(3,5,7)
4	High	(5,7,9)
5	Very High	(7,9,9)

Figure 4 also shows the triangular fuzzy number shape with its lower (a), mean (b) and upper bound (c) values [37]. Fuzzy numbers can also be represented by alternative distributions, but it was decided to use the triangular distribution for the sake of simplicity.

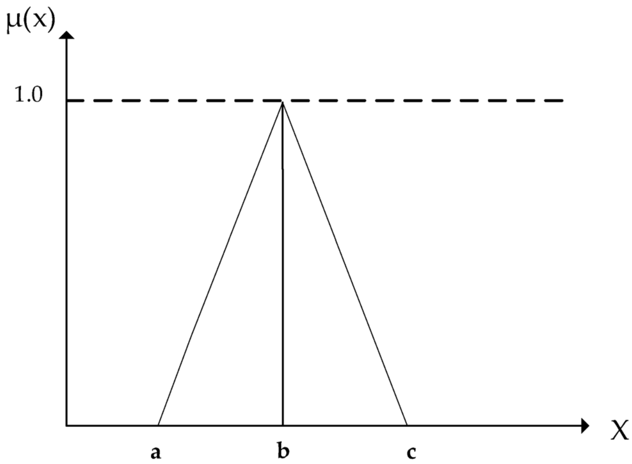

Figure 4. Illustration of the generic triangular fuzzy number.

The steps associated with the creation of a combined decision matrix were omitted, as this paper did not make use of multiple stakeholders to rank industrial symbiosis scenarios. As a result, the first step of the fuzzy TOPSIS involved the creation of a single decision matrix with the integration scenarios and associated indicator scores. The second step was to create a normalised fuzzy decision matrix, represented by Equation (1) ($i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$).

$$R = [\widetilde{r}_{ij}]_{m*n} \tag{1}$$

Each indicator was classified as a beneficial or non-beneficial criteria and normalised using Equation (2) and Equation (3), respectively.

$$\widetilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \quad c_j^* = \max_i\{c_{ij}\} \tag{2}$$

$$\widetilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \quad a_j^- = \min_i\{a_{ij}\} \tag{3}$$

Step three included the creation of a weighted normalised fuzzy decision matrix. Equation (4) was used to multiply each indicator weighting with a fuzzy indicator weighting (w_j) as determined by the user. Alakaş et al. [31] calculated industrial symbiosis indicator weights by consulting industry experts and by using a multi-criteria decision-making method. In this paper, three different indicator weighting sets were selected to illustrate the impact of indicator weighting on the final scenario rankings. This was discussed in more detail during the theoretical scenario evaluations.

$$\widetilde{v}_{ij} = \widetilde{r}_{ij} \times w_j \tag{4}$$

Step four involved calculating fuzzy positive ideal solution (FPIS, A^*) and fuzzy negative ideal solution (FNIS, A^-) values. Equations (5) and (6) were used.

$$A^* = (\widetilde{v}_1^*, \widetilde{v}_2^*, \ldots, \widetilde{v}_n^*),\ \widetilde{v}_j^* = \max_i\{v_{ij3}\} \tag{5}$$

$$A^- = (\widetilde{v}_1^-, \widetilde{v}_2^-, \ldots, \widetilde{v}_n^-),\ \widetilde{v}_j^- = \min_i\{v_{ij1}\} \tag{6}$$

The value of v_{ij3} referred to the c component value of a fuzzy number and v_{ij1} referred to the a component. This means that A^* was defined as the weighted fuzzy indicator value with the largest c component value and A^- was the weighted fuzzy indicator value with the smallest a component. Step five was used to calculate the distance from each alternative scenario to the FPIS and FNIS values. Equation (7) was used to create two matrices of results.

$$d(\tilde{x}, \tilde{y}) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \tag{7}$$

The result matrix showing the distance of each scenario to the FPIS value was obtained by populating Equation (7) with the weighted normalised fuzzy decision matrix indicator results (a_1, b_1, c_1) and the FPIS (a_2, b_2, c_2) results. The result matrix showing the distance of each scenario to the FNIS value was similarly obtained by using FNIS (a_2, b_2, c_2) results.

The indicator values obtained for the distances from FPIS and FNIS for each scenario were summed using Equation (8) and Equation (9), respectively.

$$d_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right) \tag{8}$$

$$d_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \tag{9}$$

Lastly, the d_i^* and d_i^- values for each scenario were used to calculate the closeness coefficient (CC_i) in Equation (10).

$$\mathrm{CC}_i = \frac{d_i^-}{d_i^- + d_i^*} \tag{10}$$

The CC_i values were used for the final ranking of the industrial symbiosis potential of the evaluated scenarios.

3. Results of Industrial Integration Scenario Identification and Assessment

This section describes the theoretical plant factory integration scenarios, which were identified using Figure 2 and the developed early phase industrial symbiosis assessment method, and shows how each external industry or process is connected to the plant factory system boundary. The industrial symbiosis assessment method is applied to each of the scenarios, and the indicator rankings and fuzzy TOPSIS rankings of the scenarios are reported below.

3.1. Theoretical Plant Factory Integration Scenarios

The theoretical plant factory integration scenarios are summarised in Table 2 and indicate the points of integration which were identified for each of the scenarios. An urban agriculture system (IPF1) was selected as the first theoretical scenario. This scenario represents plant factory agriculture, which takes place in a multipurpose structure. The structure can be used for residential use, office space, restaurants or research and development. The main purpose of the scenario is that the end-user market for the plant factory biomass is located within the same structure or close enough so that transportation costs are minimised. The plant factory capacity is restricted to rooftop, basement or single-floor space of a multi-storey urban building, as agriculture is not the primary function of the building. The agrovoltaic (IPF2) scenario, in the case of an indoor plant factory, is simply a structure being used for indoor plant cultivation, which uses photovoltaic (PV) panels on the structure façade, rooftop and surrounding land to generate additional energy for the plant factory system. The scope of energy generation from the PV panels is dependent on the available rooftop and façade space of the structure and the economic feasibility is determined by the energy requirements of the plant factory [10].

The theoretical integration scenarios are also illustrated in Figure 5 to show how the plant factory and external industries are connected through the points of integration.

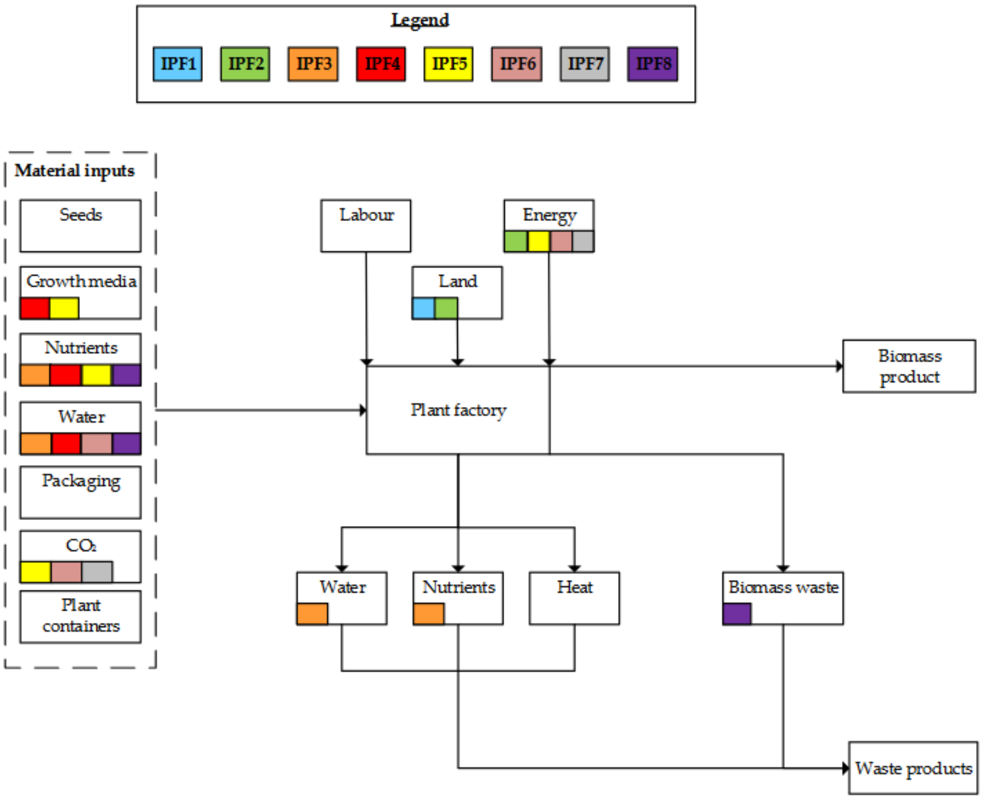

Figure 5. Updated plant factory system boundary which shows where the external industries integrate into the theoretical plant factory. Scenarios include urban agriculture (IPF1), agrovoltaics (IPF2), aquaculture (IPF3), beer brewery (IPF4), composting/digeponics (IPF5), coal-fired thermal power plant (IPF6), landfill (IPF7) and biodiesel production (IPF8).

The aquaculture (IPF3) integration scenario creates an aquaponic system. Figure 5 shows that the symbiotic relationship is strongly related to water and nutrient sharing between the aquaculture system and the plant factory. It was assumed that the aquaculture system and plant factory were simultaneously designed. This means that the scale of both systems is designed so that they provide and receive enough resources from the points of integration that connect the two systems. The brewery (IPF4) scenario supplements plant factory grow media and liquid fertiliser demands so that the plant factory can sell its biomass as organic products for a higher price. It is assumed that the plant factory receives these waste streams at a competitively low price compared to inorganic fertiliser and conventional grow media, such as soil. The plant factory site selection is assumed to be close enough to the brewery plant so that the transportation cost of the waste stream does not hinder the economic feasibility of the system integration.

The composting (IPF5) system makes use of locally available organic matter and it was assumed that the plant factory would have to pay for the transportation and processing of the organic waste. It was assumed that an in-vessel composting system was used to monitor the composting process and prevent contamination so that the fertiliser can be used in a pesticide-free plant factory system [14]. The coal-fired thermal power plant (IPF6) was assumed to be located close enough to the plant factory so that heat loss from cooling water was not detrimental to the integration feasibility. Flue gas from the power plant was assumed to provide sufficient amounts of CO_2 to elevate the CO_2 levels in the plant factory [23].

The landfill (IPF7) scenario provides the plant factory with energy and CO_2 from biogas extraction. It was assumed that the landfill was of sufficient size and composition to motivate the construction of a biogas plant, and that the biogas production lifespan of the landfill was long enough to make site selection close to the landfill viable. Lastly, Figure 5 shows how the biofuel production plant (IPF8) provides liquid fertiliser to the plant factory by collecting washing water during the biodiesel production process. It was also assumed that the plant factory was connected to the biodiesel plant by providing excess biomass waste to the biodiesel process, which can be used as feedstocks for biofuel production.

3.2. Theoretical Integration Scenario Assessment

This section presents the results of the plant factory integration assessment method, which was based on the defined integration scenarios and indicators. The first part discusses the indicator scores for each of the scenarios and is followed by the fuzzy TOPSIS analysis and ranking of the integration scenarios.

3.2.1. Theoretical Scenario Indicator Scores

As shown in Table 3, the environmental impact score of an integration scenario can be described in terms of energy, water and materials. Table A1 in Appendix A shows and motivates which of the environmental sub-indicator definitions were considered when determining the environmental impact indicator score for each of the theoretical integration scenarios. Table 5 shows the final integration potential rankings of the theoretical scenarios, as was determined by the scenario descriptions and the indicator scoring system in Table 3.

Table 5. Indicator scores and integration scenario ranking results.

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	Total	Rank
IPF1 (Urban agriculture)	3	3	1	7	7
IPF2 (Agrovoltaics)	2	2	2	6	8
IPF3 (Aquaculture)	4	3	2	9	4
IPF4 (Beer derived residue)	4	4	3	11	1
IPF5 (Composting)	3	3	4	10	2
IPF6 (Coal-fired thermal power plant)	3	4	3	10	2
IPF7 (Landfills)	4	3	2	9	4
IPF8 (Biodiesel production)	3	2	3	8	6

Based on the indicator scoring system, the beer brewery (IPF4) integration scenario had the overall best integration potential with a plant factory. The environmental and economic benefits of integrating with the brewery industry was motivated by Martin, Poulikidou and Molin [16] and Li et al. [1], respectively. The agrovoltaic (IPF2) scenario was ranked the lowest, as solar energy generation from PV panels on the façade of a building is unable to satisfy the energy requirements of a large-scale indoor plant factory facility which uses artificial lighting [10]. Motivations for the indicator scores, based on the literature, are shown in Table A2 to provide additional clarity to the way in which the indicator score definitions were applied by the authors.

The results of Table 5 show that IPF5 had a similar integration potential score to IPF6, and IPF3 was similar to IPF7. This makes it difficult to determine which scenario is most beneficial for a prospective plant factory development. In order to account for the uncertainty of the indicator score rankings, and to incorporate indicator weightings, the integration scenario scores were processed further using fuzzy TOPSIS.

3.2.2. Theoretical Scenario Fuzzy TOPSIS Scores

The integration potential indicator scores were analysed using the fuzzy TOPSIS method in Section 2.3.3. Three weighting scenarios with varying fuzzy number indicator weightings were evaluated to show the impact that indicator weightings had on integration scenario rankings. Scenario 1 used equal medium weightings (3,5,7) for the environmental, economic and network indicator scores to show zero bias towards any indicator. Scenario 2 used very high weightings (7,9,9) for economic indicator scores and medium weightings (3,5,7) for environmental and network indicator scores to show the integration scenario rankings when economics are regarded as the priority. Scenario 3 used very high weightings (7,9,9) for economic indicator scores, medium weightings (3,5,7) for environmental indicator scores and very low (1,1,3) network indicator scores. Scenario 3 represents the importance of economic viability while considering the lack of data, which the network indicator provides. The low weighting of the network indicator was selected as it could not be determined with certainty that an integration scenario with multiple points of integration would be the optimal scenario.

The intermediate steps for calculating the closeness coefficients (CC_i) and the integration scenario rankings are shown in Tables A3–A19 in Appendix A. The results of the industry integration assessment method are shown in Table 6.

Table 6. Plant factory integration scenario closeness coefficients (CC_i) and rankings.

	Weighting Scenario 1		**Weighting Scenario 2**		**Weighting Scenario 3**	
Plant Factory Integration Scenario Designation	CC_i	**Rank**	CC_i	**Rank**	CC_i	**Rank**
IPF1 (Urban agriculture)	0.2895	7	0.3204	7	0.4149	6
IPF2 (Agrovoltaics)	0.1360	8	0.1161	8	0.0554	8
IPF3 (Aquaculture)	0.5680	4	0.6311	4	0.7241	2
IPF4 (Beer derived residue)	0.8554	1	0.8766	1	0.9418	1
IPF5 (Composting)	0.7105	3	0.6796	3	0.5851	5
IPF6 (Coal-fired thermal power plant)	0.7109	2	0.6799	2	0.6869	4
IPF7 (Landfills)	0.5680	4	0.6311	4	0.7241	2
IPF8 (Biodiesel production)	0.4217	6	0.4332	6	0.3672	7
Indicator fuzzy number weightings						
Environmental	(3,5,7)		(3,5,7)		(3,5,7)	
Economic	(3,5,7)		(7,9,9)		(7,9,9)	
Network	(3,5,7)		(3,5,7)		(1,1,3)	

Despite the fuzzy TOPSIS analyses and the varying indicator weightings, the beer brewery (IPF4) integration scenario remained the top-rated scenario throughout. The robustness of this result was motivated by the literature, which proposed plant factory integration with the brewery industry to achieve economic viability and reduce environmental pollution [1,16]. The indicator scores in Table 5 led to two pairs of scenarios with equal integration potential scores. The results in Table 6 show that the fuzzy TOPSIS analyses provide a clearer scenario hierarchy with fewer scenarios scoring similar results. This was attributed to the extra complexity that fuzzy TOPSIS provided to the industrial integration assessment method.

Lastly, changing the indicator weightings caused some variations in the integration scenario rankings. While the beer brewery (IPF4) integration scenario remained the most ideal integration scenario, the composting (IPF5) integration scenario dropped from a close third-best in Scenario 1 and 2 to the fifth position in Scenario 3. This was attributed to the high number of points of integration in the composting (IPF5) integration scenario and the lower indicator weighting assigned to the network indicator in Scenario 3. The indicator weighting of Scenario 3 requires the quality of the points of integration to be represented by the environmental and economic impacts on the theoretical plant factory, instead of just focusing on the total number of points of integration between the plant factory and the external industry. Therefore, Table 6 provides rankings of plant factory integration scenarios from differing points of view.

4. Discussion

This section discusses the evaluated plant factory integration scenarios in the context of industrial symbiosis successes and challenges. The novelty and limitations of the industrial symbiosis assessment method is discussed, and future research opportunities are identified based on the methodological- and topic-related limitations.

4.1. Integration Potential of Theoretical Plant Factory Scenarios

The theoretical plant factory integration scenarios were all selected for their potential to supplement the resource demands of a plant factory, as shown in Table 2 and Figure 5. Industrial symbiosis provides a framework through which plant factories can be integrated with external industries, but it does not necessarily mean that they share the same space. The concept of urban agriculture in scenario IPF1, on the other hand, is based on the idea of sharing space between crop cultivation and normal urban activities. Thomaier et al. [20] reviewed urban agriculture literature and found that the three most common uses of buildings, which shared space for urban farming, were restaurants, research and other food-related businesses. The advantage of having fresh produce close to these businesses is that they make use of the agricultural products, either by selling them or by studying the performance of urban agricultural technologies. The environmental indicator score of IPF1 was based on the close proximity of the theoretical plant factory to the urban consumer [42]. Benis and Ferrão [3] also reviewed different urban farming designs which could be accommodated in the urban environment. They ranged from rooftop farms to building façade designs and even vertical farm skyscrapers. The proper design depends on the desired production capacity, the specific crop being cultivated and the additional uses that the building must accommodate.

The concept of agrovoltaics, IPF2, is also one which proposes a dual use for a specific space. It proposes the use of land for simultaneous crop cultivation and energy generation from solar energy. The concept is already being implemented through the installation of PV panels onto greenhouse rooftops [21,22]. The advantage of this concept is the simultaneous crop production and energy generation that can be achieved. Unfortunately for solar dependent cultivation systems, the addition of PV panels reduces solar radiation onto the crop canopy and can influence crop growth rates. This requires a balance to be maintained between crop cultivation and energy generation. The conflicting design considerations mentioned in the literature are reflected in the poor environmental and economic indicator scores of the industrial symbiosis assessment method. For an indoor plant factory, the lack of direct sunlight is not an issue if artificial lighting is used, but the energy being generated might be insignificant compared to the energy requirements of the plant factory [10].

Aquaculture systems are typically considered for integration with crop systems [18] and are commonly referred to as aquaponics in IPF3 [5]. Water is circulated through the crop system and stripped of nutrients before being introduced to the aquaculture system as clean water. Conversely, the water leaving the aquaculture system is rich in nutrients and can be recirculated back to the crop system for nutrient stripping [5]. The challenge of creating an aquaponic system is in matching the water and nutrient requirements of the fish farm with that of the crop system. In terms of water, the size and type of crop system determines how much water leaves the plant factory and can be recirculated to the aquaculture system. A mismatch in size of either the crop or fish system requires an additional supplement of water and nutrient management [43]. Kastner, Lau and Kraft [29] also concluded that industrial symbiosis based on water networks had to consider the additional piping and connection costs, water prices and contamination potential. Despite the challenges of integrating aquaculture and crop cultivation systems, the environmental benefits of recycling water and waste nutrients remain significant by preventing nutrient waste runoff and water losses.

Similarly, the beer brewing industry, IPF4, was also found to be a viable integration option for plant factories based on environmental considerations [16]. Lettuce, basil and mustard greens were grown using anaerobically digested brewery wastewater as a fertiliser substitute and showed similar crop yields to the inorganic fertiliser control in most cases [44]. Furthermore, Li et al. [1] illustrated the economic viability of beer-residue-derived fertiliser through an economic analysis of a modelled plant factory. The reported environmental benefits and economic viability are reflected in the industrial symbiosis assessment method of this paper.

Stoknes et al. [45] also investigated the use of digeponics, IPF5, which consisted of anaerobic digestion of organic matter to produce heat energy and CO_2 for an insulated greenhouse. Furthermore, the biogas digestate and compost were used to substitute fertiliser and peat requirements. The composting of organic matter has successfully provided sources of CO_2, nutrients and heat energy to plant factory studies in the past [14,15]. Thomson et al. [14] also investigated the integration of a composting system with a plant factory and reviewed the multiple agricultural activities that can provide composting materials. This was mainly limited to animal manure and sewage sludge, with a special mention of the biomass waste generated from plant factory operations. The use of organic matter can be a renewable source of CO_2 if the agricultural activities continue to produce waste material. Additionally, the valorisation of organic material extends the lifespan of landfills. Thomson et al. [14] stated that composting systems would be required to valorise the organic material and could range in complexity from static outdoor piles to indoor in-vessel composting systems with advanced process controls. Process knowledge and purification systems are also required to reduce the levels of byproducts present in the composting gas.

The economic impact of IPF6 to supplement heat, water and CO_2 demands was confirmed by Gentry [23], who investigated the integration of a plant factory with a combined heat and power (CHP) plant as part of a district heating system. The CHP plant was able to provide heating to the plant factory through the district heating infrastructure, and the waste biomass from the plant factory was used as fuel feedstock. The energy sector remains a significant producer of waste heat, especially through the use of cooling water [47], and power plants have been used as site selection criteria for the establishment of integrated plant factories in the past [48]. Gentry [23] discussed the use of flue gas from CHPs to supplement CO_2 requirements in plant factories. Power plant locations can act as site indicators, and the power plant capacity can be used to size integrated plant factories so that the heat, power and CO_2 from the power plant can fully accommodate the plant factory requirements. The use of flue gas also helps to reduce emissions originating from power plants, but will require additional purification infrastructure depending on the source of fuel being used in the power plants.

Landfill biogas production, IPF7, is another source for CO_2 enrichment, which can be used as a site selection indicator for plant factory construction. Plant factories do not require fertile ground and can therefore be built close to facilities, such as landfills [10]. Landfill biogas is a source of CO_2 and energy [18], but requires purification to remove coproduct gases [50]. The biogas production lifespan of the landfill must also be considered before deciding to use it as an integrated component of the plant factory system.

Lastly, IPF8 was evaluated based on Kohda et al. [51], who evaluated the use of discharged water from a biodiesel production plant to be used as liquid fertiliser within hydroponic systems. They concluded that biofuel wastewater was able to supplement hydroponic water requirements to a certain degree before the wastewater contamination affected plant growth. This means that biofuel wastewater needs to be measured, sterilised and supplemented with nutrients to be effectively used on a larger scale to provide water and nutrients to crop systems. The infrastructure required to integrate a plant factory with a biodiesel production plant is reflected in the poor economic indicator score for IPF8 in the assessment method.

Similarly, municipal and domestic wastewater also provides an opportunity for water, nutrient and heat recovery, and allows for site selection on the edges of urban environments [10]. Zeidler, Schubert and Vrakking [10] echoed the importance of considering these wastewater streams by concluding that an industrial symbiosis between plant factories and municipal waste streams would be easier to achieve with new developments instead of retroactively integrating plant factories with existing infrastructure. This highlighted the fact that industrial symbiosis potential could be assessed based on future developments and existing infrastructure.

4.2. Implications and Limitations of the Industrial Symbiosis Assessment Method

This paper was used to explore the industrial symbiosis potential of plant factories through the development of a multi-criteria, mixed-indicator industrial symbiosis assessment method for plant factories. Whereas previous literature has focused on the development of industrial symbiosis indicator-based evaluation methods and decision-support systems [29,30,54], the novelty of this paper is in combining the knowledge fields of plant factories, industrial symbiosis and multi-criteria decision-making to provide a novel industrial symbiosis assessment method that can be used to evaluate new and existing industrial symbiosis opportunities for plant factories, and which can be used to identify potential points of integration between plant factories and external industries, which have not been considered up to this point. The evaluation of industrial symbiosis potential in the context of economic, environmental and network considerations allows for a wider selection of integration scenarios to be considered for future plant factories, and prevents integration scenarios from being disregarded solely based on economic merits.

As this paper aimed at exploring the industrial symbiosis potential of new and existing plant factories, some of the most significant scientific contributions of this paper included:

- Providing an alternative interpretation of the isolated plant factory system boundary by exploring the interactions between plant factories and the surrounding industrial environment using an open-loop system boundary approach.
- Expanding the fields of knowledge of plant factory development and industrial symbiosis by exploring the interconnectedness of the two fields of research.

The practical contribution, for practitioners in plant factory development, is a high-level industrial integration assessment method that can aid in the decision-making process for the site selection of plant factories based on the availability of surrounding industries, and which can be used to select industries that can be developed near a plant factory in the future to improve the symbiotic relationship of industries in the area.

Throughout this research, several deficiencies were noticed in the literature and in the methodological approach of this research. These deficiencies and constraints are listed and presented below, and are used as guidance for recommendations for future research:

- Theoretical integration scenarios were defined and assessed based on literature descriptions of similar integration studies, and did not use external expert or stakeholder inputs to assess scenarios.
- The multi-criteria decision-making component of the developed assessment method only considered the use of fuzzy TOPSIS due to its computational simplicity and low requirement for external user inputs. The simplicity of a fuzzy TOPSIS analysis was deemed acceptable, as all integration scenarios were theoretical and based on reported literature case studies.
- The integration scenarios only considered one external industry to be integrated with a plant factory at a time, external industries were assumed to only connect through the plant factory and had no interactions with one another and only the integration benefit for the plant factory was considered during the assessment.
- The scenario selection did not explicitly consider various industries or processes that shared a common point of integration to find an optimal industry for each point

of integration. The differences between two scenarios that only provide the same point of integration were deemed to be too complex to be captured using an early assessment method.

- The scenarios were also not based on a fixed plant factory design and capacity. It was assumed that the plant factory capacity was appropriate in each scenario so that the proposed integration would be worthwhile. The assessment method was developed to evaluate the potential of industrial integration, so it was assumed that the plant factory capacity would be determined based on the availability of resource streams from external industries.

The multi-criteria, mixed indicator industrial symbiosis assessment method made use of generalised and high-level indicators to rank the integration potential of plant factories with specific external industries. Although the indicators in this paper were deliberately simplistic to account for the lack of data during early phase assessments, future work on assessing plant factory industrial integration can include a more detailed description of industrial integration indicators, and can be validated by applying the assessment method to real world scenarios. This can allow the assessment method to distinguish between integration scenarios which supplement similar resource demands of the plant factory. Furthermore, the assessment method can be expanded to evaluate industrial cluster development around plant factories by considering the simultaneous industrial symbiosis potential of multiple industries, and by including the interactions between external industries. The multi-criteria decision-making method can also be expanded beyond fuzzy TOPSIS by considering alternative decision-making methods, such as ANP, AHP and VIKOR, to lend robustness to the industrial symbiosis rankings of the developed assessment method.

5. Conclusions

This paper addressed the research aim posed at the start of the paper by developing a multi-criteria, mixed indicator assessment method for ranking the integration potential of plant factories with external industries. Through this method, this paper was able to explore the extent to which external industries could be integrated with a plant factory to reduce operating costs and improve overall economic viability. This was achieved by considering a plant factory as an open-loop system that had resource and waste streams that could act as connection points between plant factories and external industries. Environmental, economic and network indicators were derived and used to quantify how well specific industries could integrate with plant factories through the identified points of integration. The indicator scores were processed further using fuzzy TOPSIS to account for the uncertainty associated with indicator-based evaluations and to account for the lack of information during the early establishment phase of an industrial symbiosis network.

The industrial integration assessment method was used on a selection of theoretical integration scenarios to show its functionality and the weightings of the environmental, economic and network indicator values were varied during the fuzzy TOPSIS. The assessment method and the open-loop system approach of this paper resulted in a wide range of external industries being identified as integration options for plant factories. These integration options ranged from urban structures to agricultural processes and energy generation infrastructure, and can be used to guide future industrial development around plant factory projects by knowing how certain external industries can interact with plant factories. Furthermore, this paper identified points of integration which are present in most plant factory configurations, and allows for industrial integration to be considered as a method of supplementing the resource demands of these points of integration and lowering operating costs.

After evaluating the theoretical integration scenarios of this paper, an optimal scenario of a plant factory and beer brewing plant emerged throughout the various fuzzy TOPSIS analyses. The rankings of the remaining scenarios varied depending on the indicator weightings, which were used to motivate the robustness of the final scenario rankings.

The optimal beer brewery integration scenario had water, grow media and nutrients as identified points of integration. These points of integration were not typically considered as the primary cost drivers for plant factories, but the scenario achieved the best ranking due to the multiple points of integration which it provided, the perceived ease of integration between the beer brewery and plant factory and the combined environmental and economic impacts of supplementing the water, grow media and nutrients of the plant factory.

This paper shows how favourable integration scenarios can be created without necessarily supplementing the primary cost drivers of plant factories. This allows for a wider selection of integration scenarios to be considered when designing future plant factories.

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Appendix A

This appendix provides all the supplementary and intermediate data for the indicator selection and fuzzy TOPSIS analyses of plant factory industrial integration scenarios.

Appendix A.1. Environmental Sub-Indicator Motivation

This section provides the motivations for using specific environmental indicators to generate environmental indicator scores for integration scenarios.

Table A1. Motivations for using specific environmental sub-indicator definitions to determine the environmental indicator scores for the integration scenarios.

Integrated Plant Factory Scenario Designation	Environmental Sub-Indicator Definitions Considered	Motivation
IPF1 (Urban agriculture)	Material	The use of urban land for agricultural activities was approximated as material use
IPF2 (Agrovoltaics)	Energy and material	The multipurpose use of land was considered a material environmental benefit and the solar energy generation was considered an energy valorisation intervention
IPF3 (Aquaculture)	Water and material	The identified points of integration between a plant factory and aquaculture system included water and nutrients (material)
IPF4 (Beer derived residue)	Water and material	The identified points of integration between a plant factory and the beer brewing industry included fertiliser material, grow media and treated wastewater
IPF5 (Composting)	Energy and material	The identified points of integration between a plant factory and the in-vessel composting system included composting material, heat and CO_2 resource streams

Table A1. *Cont.*

Integrated Plant Factory Scenario Designation	Environmental Sub-Indicator Definitions Considered	Motivation
IPF6 (Coal-fired thermal power plant)	Energy, water and material	Waste heat, cooling water and CO_2 was identified as energy, water and material streams, respectively
IPF7 (Landfills)	Energy and material	Energy was considered due to methane emissions from landfills and material was represented by the CO_2 emissions from anaerobic digestion which takes place inside the landfills
IPF8 (Biodiesel production)	Water and material	The discharge water from biodiesel production was classified as water and material as it could be used as liquid fertiliser, while biomass waste from the plant factory was also classified as materials

Appendix A.2. Indicator Score Motivations

This section elaborates on the motivations for awarding specific indicator scores to the theoretical plant factory integration scenarios and shows the references which were used to justify the indicator scores.

Table A2. Motivations for each of the indicator score values of the integration scenarios.

Integrated Plant Factory Scenario Designation	Environmental Motivation	Economic Motivation	Network Motivation
IPF1 (Urban agriculture)	• It was decided that the original purpose of space, or land, was to be used to the benefit of human activities in the area • Close proximity of the plant factory to the end-user market also reduces transportation requirements [42] • Urban agriculture reduces dependence and strain on fertile land [3]	• Modelled plant factories show economic feasibility in urban areas while providing fresh produce [1] • Profitability has high risk and is dependent on appropriate crop selection, plant factory design and site selection within the urban environment [1,42]	• Land was identified as the primary point of integration between the theoretical plant factory and the urban environment. The plant factory shares utilities (water and electricity) in the structure, but these utilities are assumed to not be recovered waste streams
IPF2 (Agrovoltaics)	• Generates power from solar energy but requires significant capital investments into infrastructure [21,22]	• Solar energy capture on plant factory facades have shown to mitigate negligible amounts of plant factory energy requirements [10]	• The theoretical plant factory was combined on the same land as solar power generating infrastructure and would benefit from the energy being produced
IPF3 (Aquaculture)	• The aquaculture system provided water to the plant factory to be used as part of the primary process within the factory and was given a water environmental score of five • The nutrients produced within the aquaculture system could require purification and supplements to meet crop demands and was given a material environmental score of three [29,43] • An average environmental score of four was selected for the aquaculture scenario	• The aquaculture and plant factory system required connecting infrastructure and monitoring [29] • Required personnel skilled in aquaculture and crop production • Water costs and horticultural consumables have a moderate economic impact on plant factory operations [10]. Integration would require favourable economic arrangements	• The theoretical plant factory was connected to an aquaculture system through a waste nutrient solution stream to recover water and nutrients [18]

Table A2. *Cont.*

Integrated Plant Factory Scenario Designation	Environmental Motivation	Economic Motivation	Network Motivation
IPF4 (Beer derived residue)	• Water, energy and material can be recovered from brewery wastewater [44]. This constituted a score of four based on the water sub-indicator • Raw wastewater and anaerobically digested wastewater from a beer brewery proved to increase biomass yields when used as fertiliser. Material pretreatment (anaerobic digestion) improved biomass yield compared to raw wastewater use. This constituted a score of four points based on material sub-indicator [44] • Heat energy was not included as a separate point of integration as it is specifically dependent on anaerobic digestion of brewery wastewater • Brewers' spent grains reduced environmental impact (CO_2 equivalent emissions) compared to conventional soil-based growing media [16]	• The two most promising economic models for a plant factory included the use of beer-derived fertiliser [1]	• The theoretical plant factory was connected to a beer brewery plant through a nutrient-rich wastewater stream and waste material capable of being used for fertiliser and grow media
IPF5 (Composting)	• Organic waste material was valorised to produce energy (methane). Energy score of two was assigned as anaerobic digestion infrastructure was required for energy generation • Organic material can be valorised with varying degrees of pretreatment complexity and will still deliver composting material and CO_2 [14]. A material sub-indicator score of four was awarded for material use • Prioritisation of energy will lead to anaerobic digestion infrastructure [45], while aerobic digestion will provide composting material and CO_2 as the main products [14] • An average environmental score of three was given	• Feedstock contamination and feedstock variability makes process optimisation difficult [46] • The combined cost reduction of heat, horticultural consumables and CO_2 elevation in Table 1 will have a moderate economic impact on plant factory operations	• The theoretical plant factory was connected to an in-vessel composting system which used organic waste material to provide a stabilised composting material, heat and CO_2
IPF6 (Coal-fired thermal power plant)	• The integration of the wastewater cooling stream reduces thermal pollution of the environment and lowers fuel oil dependence, and CO_2 emissions, of industrial symbiosis partners [48]. Energy- and water scores of three were assigned as thermal pollution is difficult to avoid completely • Flue gas containing CO_2 requires separation and purification. A material score of three was given	• Water and CO_2 costs, in Table 1, are moderately significant • Energy costs are significant, according to Table 1, but waste heat utilisation requires infrastructure investment and is limited by distance • An economic score of four was awarded to represent the moderate economic benefit which could be achieved under specific scenarios	• The theoretical plant factory was connected to a coal-fired thermal power plant through a cooling water stream, which provides waste heat and water [47,48], and a flue gas stream which provides CO_2 [23]

Table A2. *Cont.*

Integrated Plant Factory Scenario Designation	Environmental Motivation	Economic Motivation	Network Motivation
IPF7 (Landfills)	• The use of methane emissions from landfills for energy and CO_2 generation lowers the environmental impact of landfill emissions [18] • A material impact score of four, based on CO_2, was assigned and an energy score of four was awarded due to the energy generation systems which were required [18,50]	• The combined heat energy and CO_2 provided to the theoretical plant factory, based on Table 1 costs, can have minimal to moderate economic benefits. An economic score of three was awarded	• Heat energy and CO_2 was identified as plant factory points of integration
IPF8 (Biodiesel production)	• A water score of four was assigned as material was recovered from the biodiesel wastewater • A material score of two was assigned as significant sterilisation is required to prevent microorganism growth [51] • A combined environmental score of three was used to represent the scenario	• Discharge water from biodiesel production is not widely used as liquid fertiliser. It also requires sterilisation and nutrient supplements to meet plant growth demands [51] • An economic score of two was selected to represent the technical challenges	• Biodiesel discharge water was considered as a source of water and plant nutrients • Biomass waste from the plant factory was considered as a biodiesel feedstock

Appendix A.3. Universal Fuzzy TOPSIS Data Tables

This section provides the intermediate fuzzy TOPSIS results of integration scenarios prior to the addition of indicator weightings.

Table A3. Decision matrix fuzzy number indicator scores of the integration scenarios.

Integrated Plant Factory Scenario Designation	Environmental Score			Economic Score			Network Score		
Fuzzy number	a	b	c	a	b	c	a	b	c
IPF1 (Urban agriculture)	3	5	7	3	5	7	1	1	3
IPF2 (Agrovoltaics)	1	3	5	1	3	5	1	3	5
IPF3 (Aquaculture)	5	7	9	3	5	7	1	3	5
IPF4 (Beer derived residue)	5	7	9	5	7	9	3	5	7
IPF5 (Composting)	3	5	7	3	5	7	5	7	9
IPF6 (Coal-fired thermal power plant)	3	5	7	5	7	9	3	5	7
IPF7 (Landfills)	5	7	9	3	5	7	1	3	5
IPF8 (Biodiesel production)	3	5	7	1	3	5	3	5	7
Weighting	3	5	7	3	5	7	3	5	7

Table A4. Normalised fuzzy decision matrix using Equations (2) and (3).

	Beneficial			Beneficial			Beneficial		
Integrated Plant Factory Scenario Designation	**Environmental Score**			**Economic Score**			**Network Score**		
Fuzzy number	a	b	c	a	b	c	a	b	c
IPF1 (Urban agriculture)	0.3333	0.5556	0.7778	0.3333	0.5556	0.7778	0.1111	0.1111	0.3333
IPF2 (Agrovoltaics)	0.1111	0.3333	0.5556	0.1111	0.3333	0.5556	0.1111	0.3333	0.5556
IPF3 (Aquaculture)	0.5556	0.7778	1.0000	0.3333	0.5556	0.7778	0.1111	0.3333	0.5556
IPF4 (Beer derived residue)	0.5556	0.7778	1.0000	0.5556	0.7778	1.0000	0.3333	0.5556	0.7778
IPF5 (Composting)	0.3333	0.5556	0.7778	0.3333	0.5556	0.7778	0.5556	0.7778	1.0000
IPF6 (Coal-fired thermal power plant)	0.3333	0.5556	0.7778	0.5556	0.7778	1.0000	0.3333	0.5556	0.7778
IPF7 (Landfills)	0.5556	0.7778	1.0000	0.3333	0.5556	0.7778	0.1111	0.3333	0.5556
IPF8 (Biodiesel production)	0.3333	0.5556	0.7778	0.1111	0.3333	0.5556	0.3333	0.5556	0.7778

Appendix A.4. Equal Weighting Fuzzy TOPSIS Data Tables

This section summarises the intermediate and final results of the fuzzy TOPSIS integration scenario rankings using equal indicator weightings.

Table A5. Weighted normalised fuzzy decision matrix using Equation (4).

	Beneficial			Beneficial			Beneficial		
Integrated Plant Factory Scenario Designation	**Environmental Score**			**Economic Score**			**Network Score**		
Fuzzy number	a	b	c	a	b	c	a	b	c
IPF1 (Urban agriculture)	1.0000	2.7778	5.4444	1.0000	2.7778	5.4444	0.3333	0.5556	2.3333
IPF2 (Agrovoltaics)	0.3333	1.6667	3.8889	0.3333	1.6667	3.8889	0.3333	1.6667	3.8889
IPF3 (Aquaculture)	1.6667	3.8889	7.0000	1.0000	2.7778	5.4444	0.3333	1.6667	3.8889
IPF4 (Beer derived residue)	1.6667	3.8889	7.0000	1.6667	3.8889	7.0000	1.0000	2.7778	5.4444
IPF5 (Composting)	1.0000	2.7778	5.4444	1.0000	2.7778	5.4444	1.6667	3.8889	7.0000
IPF6 (Coal-fired thermal power plant)	1.0000	2.7778	5.4444	1.6667	3.8889	7.0000	1.0000	2.7778	5.4444
IPF7 (Landfills)	1.6667	3.8889	7.0000	1.0000	2.7778	5.4444	0.3333	1.6667	3.8889
IPF8 (Biodiesel production)	1.0000	2.7778	5.4444	0.3333	1.6667	3.8889	1.0000	2.7778	5.4444
Weighting	3	5	7	3	5	7	3	5	7

Table A6. Fuzzy positive ideal solution (FPIS, A^*) and fuzzy negative ideal solution (FNIS, A^-) values using Equations (5) and (6).

	Beneficial			Beneficial			Beneficial		
Integrated Plant Factory Scenario Designation	**Environmental Score**			**Economic Score**			**Network Score**		
Fuzzy number	a	b	c	a	b	c	a	b	c
A^*	1.6667	3.8889	7.0000	1.6667	3.8889	7.0000	1.6667	3.8889	7.0000
A^-	0.3333	1.6667	3.8889	0.3333	1.6667	3.8889	0.3333	0.5556	2.3333

Table A7. Scenario distances from fuzzy positive ideal solution (FPIS, A^*) and summed (d_i^*) distance, using Equations (7) and (8).

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	d_i^*
IPF1 (Urban agriculture)	1.1689	1.1689	3.3993	5.7371
IPF2 (Agrovoltaics)	2.3377	2.3377	2.3377	7.0132
IPF3 (Aquaculture)	0.0000	1.1689	2.3377	3.5066
IPF4 (Beer derived residue)	0.0000	0.0000	1.1689	1.1689
IPF5 (Composting)	1.1689	1.1689	0.0000	2.3378
IPF6 (Coal-fired thermal power plant)	1.1689	0.0000	1.1689	2.3378
IPF7 (Landfills)	0.0000	1.1689	2.3377	3.5066
IPF8 (Biodiesel production)	1.1689	2.3377	1.1689	4.6755

Table A8. Scenario distances from fuzzy negative ideal solution (FNIS, A^-) and summed (d_i^-) distance, using Equations (7) and (9).

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	d_i^-
IPF1 (Urban agriculture)	1.1689	1.1689	0.0000	2.3377
IPF2 (Agrovoltaics)	0.0000	0.0000	1.1037	1.1037
IPF3 (Aquaculture)	2.3377	1.1689	1.1037	4.6103
IPF4 (Beer derived residue)	2.3377	2.3377	2.2407	6.9161
IPF5 (Composting)	1.1689	1.1689	3.3993	5.7371
IPF6 (Coal-fired thermal power plant)	1.1689	2.3377	2.2407	5.7473
IPF7 (Landfills)	2.3377	1.1689	1.1037	4.6103
IPF8 (Biodiesel production)	1.1689	0.0000	2.2407	3.4096

Table A9. Closeness coefficient (CC_i) and final integration scenario ranking using equal indicator weightings and Equation (10).

Integrated Plant Factory Scenario Designation	d_i^*	d_i^-	CC_i	Rank
IPF1 (Urban agriculture)	5.7371	2.3377	0.2895	7
IPF2 (Agrovoltaics)	7.0132	1.1037	0.1360	8
IPF3 (Aquaculture)	3.5066	4.6103	0.5680	4
IPF4 (Beer derived residue)	1.1689	6.9161	0.8554	1
IPF5 (Composting)	2.3378	5.7371	0.7105	3
IPF6 (Coal-fired thermal power plant)	2.3378	5.7473	0.7109	2
IPF7 (Landfills)	3.5066	4.6103	0.5680	4
IPF8 (Biodiesel production)	4.6755	3.4096	0.4217	6

Appendix A.5. Very High Economic Indicator Weighting Fuzzy TOPSIS Data Tables

This section summarises the intermediate and final results of the fuzzy TOPSIS integration scenario rankings using very high economic indicator weightings.

Table A10. Weighted normalised fuzzy decision matrix using Equation (4) with a focus on economic impact.

	Beneficial			Beneficial			Beneficial		
Integrated Plant Factory Scenario Designation	**Environmental Score**			**Economic Score**			**Network Score**		
Fuzzy number	a	b	c	a	b	c	a	b	c
IPF1 (Urban agriculture)	2.3333	5.0000	7.0000	1.0000	2.7778	5.4444	0.3333	0.5556	2.3333
IPF2 (Agrovoltaics)	0.7778	3.0000	5.0000	0.3333	1.6667	3.8889	0.3333	1.6667	3.8889
IPF3 (Aquaculture)	3.8889	7.0000	9.0000	1.0000	2.7778	5.4444	0.3333	1.6667	3.8889
IPF4 (Beer derived residue)	3.8889	7.0000	9.0000	1.6667	3.8889	7.0000	1.0000	2.7778	5.4444
IPF5 (Composting)	2.3333	5.0000	7.0000	1.0000	2.7778	5.4444	1.6667	3.8889	7.0000
IPF6 (Coal-fired thermal power plant)	2.3333	5.0000	7.0000	1.6667	3.8889	7.0000	1.0000	2.7778	5.4444
IPF7 (Landfills)	3.8889	7.0000	9.0000	1.0000	2.7778	5.4444	0.3333	1.6667	3.8889
IPF8 (Biodiesel production)	2.3333	5.0000	7.0000	0.3333	1.6667	3.8889	1.0000	2.7778	5.4444
Weighting	7	9	9	3	5	7	3	5	7

Table A11. Fuzzy positive ideal solution (FPIS, A^*) and fuzzy negative ideal solution (FNIS, A^-) values with a focus on economic impact and using Equations (5) and (6).

	Beneficial			Beneficial			Beneficial		
Integrated Plant Factory Scenario Designation	**Environmental Score**			**Economic Score**			**Network Score**		
Fuzzy number	a	b	c	a	b	c	a	b	c
A^*	3.8889	7.0000	9.0000	1.6667	3.8889	7.0000	1.6667	3.8889	7.0000
A^-	0.7778	3.0000	5.0000	0.3333	1.6667	3.8889	0.3333	0.5556	2.3333

Table A12. Scenario distances from fuzzy positive ideal solution (FPIS, A^*) and summed (d_i^*) distance with a focus on economic impact, using Equations (7) and (8).

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	d_i^*
IPF1 (Urban agriculture)	1.8637	1.1689	3.3993	6.4319
IPF2 (Agrovoltaics)	3.7273	2.3377	2.3377	8.4028
IPF3 (Aquaculture)	0.0000	1.1689	2.3377	3.5066
IPF4 (Beer derived residue)	0.0000	0.0000	1.1689	1.1689
IPF5 (Composting)	1.8637	1.1689	0.0000	3.0325
IPF6 (Coal-fired thermal power plant)	1.8637	0.0000	1.1689	3.0325
IPF7 (Landfills)	0.0000	1.1689	2.3377	3.5066
IPF8 (Biodiesel production)	1.8637	2.3377	1.1689	5.3703

Table A13. Scenario distances from fuzzy negative ideal solution (FNIS, A^-) and summed (d_i^-) distance with a focus on economic impact, using Equations (7) and (9).

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	d_i^-
IPF1 (Urban agriculture)	1.8637	1.1689	0.0000	3.0325
IPF2 (Agrovoltaics)	0.0000	0.0000	1.1037	1.1037
IPF3 (Aquaculture)	3.7273	1.1689	1.1037	5.9999
IPF4 (Beer derived residue)	3.7273	2.3377	2.2407	8.3057
IPF5 (Composting)	1.8637	1.1689	3.3993	6.4319
IPF6 (Coal-fired thermal power plant)	1.8637	2.3377	2.2407	6.4421
IPF7 (Landfills)	3.7273	1.1689	1.1037	5.9999
IPF8 (Biodiesel production)	1.8637	0.0000	2.2407	4.1043

Table A14. Closeness coefficient (CC_i) and final integration scenario ranking using equal indicator weightings with a focus on economic impact and using Equation (10).

Integrated Plant Factory Scenario Designation	d_i^*	d_i^-	CC_i	Rank
IPF1 (Urban agriculture)	6.4319	3.0325	0.3204	7
IPF2 (Agrovoltaics)	8.4028	1.1037	0.1161	8
IPF3 (Aquaculture)	3.5066	5.9999	0.6311	4
IPF4 (Beer derived residue)	1.1689	8.3057	0.8766	1
IPF5 (Composting)	3.0325	6.4319	0.6796	3
IPF6 (Coal-fired thermal power plant)	3.0325	6.4421	0.6799	2
IPF7 (Landfills)	3.5066	5.9999	0.6311	4
IPF8 (Biodiesel production)	5.3703	4.1043	0.4332	6

Appendix A.6. Very High Economic Indicator Weighting and Low Network Indicator Weighting Fuzzy TOPSIS Data Tables

This section summarises the intermediate and final results of the fuzzy TOPSIS integration scenario rankings using very high economic indicator weightings and low network indicator weightings.

Table A15. Weighted normalised fuzzy decision matrix using Equation (4) with a focus on economic impact and low focus on network connections.

	Beneficial			Beneficial			Beneficial		
Integrated Plant Factory Scenario Designation	Environmental Score			Economic Score			Network Score		
Fuzzy number	a	b	c	a	b	c	a	b	c
IPF1 (Urban agriculture)	2.3333	5.0000	7.0000	1.0000	2.7778	5.4444	0.1111	0.1111	1.0000
IPF2 (Agrovoltaics)	0.7778	3.0000	5.0000	0.3333	1.6667	3.8889	0.1111	0.3333	1.6667
IPF3 (Aquaculture)	3.8889	7.0000	9.0000	1.0000	2.7778	5.4444	0.1111	0.3333	1.6667
IPF4 (Beer derived residue)	3.8889	7.0000	9.0000	1.6667	3.8889	7.0000	0.3333	0.5556	2.3333
IPF5 (Composting)	2.3333	5.0000	7.0000	1.0000	2.7778	5.4444	0.5556	0.7778	3.0000
IPF6 (Coal-fired thermal power plant)	2.3333	5.0000	7.0000	1.6667	3.8889	7.0000	0.3333	0.5556	2.3333

Table A15. *Cont.*

Integrated Plant Factory Scenario Designation	Beneficial			Beneficial			Beneficial		
	Environmental Score			Economic Score			Network Score		
IPF7 (Landfills)	3.8889	7.0000	9.0000	1.0000	2.7778	5.4444	0.1111	0.3333	1.6667
IPF8 (Biodiesel production)	2.3333	5.0000	7.0000	0.3333	1.6667	3.8889	0.3333	0.5556	2.3333
Weighting	7	9	9	3	5	7	1	1	3

Table A16. Fuzzy positive ideal solution (FPIS, A^*) and fuzzy negative ideal solution (FNIS, A^-) values with a focus on economic impact, low focus on network connections and using Equations (5) and (6).

Integrated Plant Factory Scenario Designation	Beneficial			Beneficial			Beneficial		
	Environmental Score			Economic Score			Network Score		
Fuzzy number	a	b	c	a	b	c	a	b	c
A^*	3.8889	7.0000	9.0000	1.6667	3.8889	7.0000	0.5556	0.7778	3.0000
A^-	0.7778	3.0000	5.0000	0.3333	1.6667	3.8889	0.1111	0.1111	1.0000

Table A17. Scenario distances from fuzzy positive ideal solution (FPIS, A^*) and summed (d_i^*) distance with a focus on economic impact and low focus on network connections, using Equations (7) and (8).

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	d_i^*
IPF1 (Urban agriculture)	1.8637	1.1689	1.2439	4.2765
IPF2 (Agrovoltaics)	3.7273	2.3377	0.8510	6.9161
IPF3 (Aquaculture)	0.0000	1.1689	0.8510	2.0199
IPF4 (Beer derived residue)	0.0000	0.0000	0.4255	0.4255
IPF5 (Composting)	1.8637	1.1689	0.0000	3.0325
IPF6 (Coal-fired thermal power plant)	1.8637	0.0000	0.4255	2.2892
IPF7 (Landfills)	0.0000	1.1689	0.8510	2.0199
IPF8 (Biodiesel production)	1.8637	2.3377	0.4255	4.6269

Table A18. Scenario distances from fuzzy negative ideal solution (FNIS, A^-) and summed (d_i^-) distance with a focus on economic impact and low focus on network connections, using Equations (7) and (9).

Integrated Plant Factory Scenario Designation	Environmental Score	Economic Score	Network Score	d_i^-
IPF1 (Urban agriculture)	1.8637	1.1689	0.0000	3.0325
IPF2 (Agrovoltaics)	0.0000	0.0000	0.4057	0.4057
IPF3 (Aquaculture)	3.7273	1.1689	0.4057	5.3019
IPF4 (Beer derived residue)	3.7273	2.3377	0.8215	6.8866
IPF5 (Composting)	1.8637	1.1689	1.2439	4.2765
IPF6 (Coal-fired thermal power plant)	1.8637	2.3377	0.8215	5.0229
IPF7 (Landfills)	3.7273	1.1689	0.4057	5.3019
IPF8 (Biodiesel production)	1.8637	0.0000	0.8215	2.6852

Table A19. Closeness coefficient (CC_i) and final integration scenario ranking with a focus on economic impact and low focus on network connections, using Equation (10).

Integrated Plant Factory Scenario Designation	d_i^*	d_i^-	CC_i	Rank
IPF1 (Urban agriculture)	4.2765	3.0325	0.4149	6
IPF2 (Agrovoltaics)	6.9161	0.4057	0.0554	8
IPF3 (Aquaculture)	2.0199	5.3019	0.7241	2
IPF4 (Beer derived residue)	0.4255	6.8866	0.9418	1
IPF5 (Composting)	3.0325	4.2765	0.5851	5
IPF6 (Coal-fired thermal power plant)	2.2892	5.0229	0.6869	4
IPF7 (Landfills)	2.0199	5.3019	0.7241	2
IPF8 (Biodiesel production)	4.6269	2.6852	0.3672	7

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