Energy-use Efficiency Optimization for Hydroponics Component of Indoor Aquaponics

by

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ABSTRACT

The soaring global population has put an immense burden on the scientific world to develop ingenious sustainable food production systems. Aquaponics, an emerging alternative to traditional farming practice, promises to offer a sustainable and efficient solution to this problem, though its economic viability is still being tested. A merger between aquaculture and hydroponics, the aquaponics technique utilizes aquaculture effluent to grow plants. However, implementing a large-scale indoor aquaponics system faces multiple challenges, both from the technical and economic aspects, one of which is related to excessive energy consumption. As the hydroponic component utilizes a significant portion of this energy, this study aims at optimizing the energy-use efficiency of indoor plant production systems within the aquaponics facility. The research progresses through three phases. The first phase follows a systematic approach to reviewing the current literature on energy efficiency in indoor aquaponics. It puts emphasis on recording characteristics related to artificial illuminance – types, specific wavelengths, photoperiod, daily light integral, and switching frequency. The second phase aims to revise the existing aquaponics ontology model with relevant system knowledge related to energy consumption and further develop an interactive graphical user interface with data populated from the new ontology model, providing a step-by-step guide on creating the energy-efficient aquaponics system. The third phase compares the energy-use efficiency of two different hydroponic systems (Nutrient film technique and deep-water culture) within the aquaponics facility. Further, it evaluates the impact of the light recipe on the growth and characteristics of the *Lactuca sativa L.* (Little Gem) plantation. In addition, this research throws light on smart monitoring applications that enhance energy-use efficiency and proposes various emerging technologies within aquaponics that may offer economic, social, and environmental

sustainability while delivering food security and nutrition for all, thus paving the way towards a cleaner food production system.

PREFACE

This thesis is the original work by Syed Abreez Gillani. Two journal papers and two conference papers related to this thesis have been submitted or published and are listed below. This thesis is organized in paper format by following the paper-based thesis guideline.

1. **Syed Abreez Gillani,** Rabiya Abbasi, Pablo Martinez, Rafiq Ahmad, "Review on Energy Efficient Artificial Illumination in Aquaponics" *Journal of Cleaner and Circular Bioeconomy.* Available at ScienceDirect: https://doi.org/10.1016/j.clcb.2022.100015

   Syed Abreez Gillani performed the literature review while Rabiya Abbasi provided the guidance for the review methodology.

2. **Syed Abreez Gillani,** Rabiya Abbasi, Pablo Martinez, Rafiq Ahmad, "Ontology-based Interactive Learning Approach for Transdisciplinary Teaching in Learning Factories" *12th Conference on Learning Factories, CLF 2022*. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4071925

   Syed Abreez Gillani updated the existing ontology model under the guidance of Rabiya Abbasi. Syed further designed the graphical user interface and performed the survey.

3. **Syed Abreez Gillani,** Rabiya Abbasi, Pablo Martinez, Rafiq Ahmad, "Comparison of Energy-use Efficiency for Lettuce Plantation under Nutrient Film Technique and Deep-Water Culture Hydroponic Systems" *International Conference on Industry 4.0 and Smart Manufacturing.* (Under review)

   Syed Abreez Gillani was responsible for conducting the experiments while Rabiya Abbasi assisted with data collection.

4. **Syed Abreez Gillani,** Pablo Martinez, Rafiq Ahmad, "Comparison of Energy-use Efficiency for Lettuce Plantation under Varying Hydroponic Conditions" *Smart Agriculture Technology*. (Under review)

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First and foremost, I would like to praise and thank Almighty God for granting me countless blessings, knowledge, and the opportunity to accomplish this thesis.

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Finally, I am forever indebted to my beloved parents, Syed Mohammad Ashraf Gillani and Mahjoob-un-Nisa, for their unfailing love, support, and encouragement which have been essential to undertaking this journey and succeeding in the program. To my sister, Syed Qaaifah Gillani, for keeping me focused and on track. Lastly, a special thanks to my best friend forever, Syed Shireen Andrabi, for always believing in me and giving me extra strength to get things done.

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LIST OF ABBREVIATIONS

EUE	Energy-Use Efficiency
LED	Light Emitting Diode
FLO	Fluorescent Lamps
HID	High-Intensity Discharge Lamps
IND	Induction Lamps
PAR	Photosynthetically Active Radiation
DLI	Daily Light Integral
PPF	Photosynthetic Photon Flux
PPFD	Photosynthetic Photon Flux Density
IoT	Internet of Things

Chapter 1 Introduction

The first chapter organizes the thesis, describes the work done, and provides motivation for the research. By defining the preliminary research questions, this chapter establishes the objectives of this research project.

1.1 Background and Motivation

Unsustainable world population growth has exacerbated resource scarcity. A recent study conducted by the United Nations projected the human population to reach a staggering 10 billion people by the year 2050 [1], as compared to the present 7.9 billion figure [2]. This is bound to place an additional burden on our food and agricultural system, and with the traditional farming practices, the resources required to cater to such a population seem vulnerable. An estimated 40% of the available land area is used for agriculture alone, which patently represents the inefficiency of the traditional farming system [3]. Additionally, agricultural irrigation is believed to consume 70% of available freshwater resources [4].

As per the food and agriculture organization of the United Nations (FAO), nearly 8.9% of the world's population, or roughly 690 million people, are hungry or lack food security [5]. Of this estimated number, 135 million suffer from acute hunger, and COVID-19 is believed to double that number in the coming years, putting an additional 135 million people at risk of acute hunger [6]. These challenges pose an imminent threat to society and thus call for a more resource and energy-efficient sustainable food production system.

The United Nations general assembly adopted the 2030 agenda for sustainable development that includes seventeen sustainable development goals (SDGs). The second goal in the list, named “zero hunger” aims at establishing a sustainable food production system, a vision of implementing resilient agricultural practices that increase productivity and production while maintaining the ecosystem and fighting against climate change [7].

1.2 Sustainable Food Production System

The resource use efficiency poses a significant challenge for intensively managed agricultural systems that incorporate high external inputs. Genetic improvements and the use of external inputs such as energy, pesticides, or fertilizers led to increased productivity of agricultural systems in the past [8]. However, sustainable agriculture requires developing plant production systems that are highly resource-efficient while being ecologically safe and socially acceptable.

The growing environmental impact of traditional farming practices has aroused interest in urban agriculture and plant factories, predominantly because of reduced waste and its transportation energy usage [9]. However, due to the high energy costs associated with the lighting system, there arises a need to offer energy-efficient solutions [10]. New forms of urban agricultural systems such as rooftop greenhouses have been developed but are limited by the economic viability due to the current building legislation for adapting greenhouse structures [11], [12]. At the same time, various solutions to the growing food crisis in the context of sustainability have been proposed in the past [13], and a holistic approach to enhancing urban agriculture efficiency and optimizing the overall resource consumption is lacking.

With the urban population expected to grow further, people's food requirements at the lowest environmental and energy costs can be made possible through sustainable food production systems [14]. Aquaponic farming concepts that comprise of aquaponics, a merger of tank-based aquaculture with hydroponics, and trans-aquaponics, a merger of tankless aquaculture with non-hydroponic plant cultivation, have been discussed recently [15]. Such systems may offer economic, social, and environmental sustainability while delivering food security and nutrition for all, thus paving the way toward a cleaner food production system [16].

1.3 Aquaponics – A Resource-Efficient Alternative

A plausible alternative to challenges associated with food security lies in the sustainable intensification of agricultural practices worldwide, and aquaponics promises to be a technology that has evolved over the recent years to optimize resource use efficiency and maintain the ecosystem balance [17]. Aquaponics is defined as a merger between aquaculture and hydroponics, a technique that utilizes aquaculture effluent to grow plants [18]. As depicted in Figure 1-1, aquaponics comprises a recirculating aquaculture system (RAS), a hydroponics component, and a biofilter comprising of microbial community [19]. The waste excreted by fish constituted of ammonia (NH_3^+) along with other constituents is converted by selected microbes to nitrates (NO_3^-). This enriched effluent is then pumped into the hydroponic component of the system, where the nutrients are readily available for uptake. Eliminating the need for soil, hydroponics provides the plant roots with direct access to nitrates, oxygen, and water and thus helps in the rapid growth of plants. As the waste produced in aquaculture is used as raw input for hydroponics components, aquaponics is adept at emulating symbiotic natural systems.

Aquaponic systems are more productive annually as they are implacable by seasonal changes and harsh weather conditions. Based on the topology of the building enclosure, these systems are generally classified as indoor or greenhouse aquaponics [20]. Indoor aquaponic systems require artificial illuminance and an active control system for heating, cooling, and ventilation that increases energy requirements, carbon footprint, and operational costs [21]. However, such systems can be operated year-round, unlike greenhouse aquaponic facilities that offer commercially feasible operations only in temperate regions with mild winter and summer climates due to their limited environmental control capability [20].

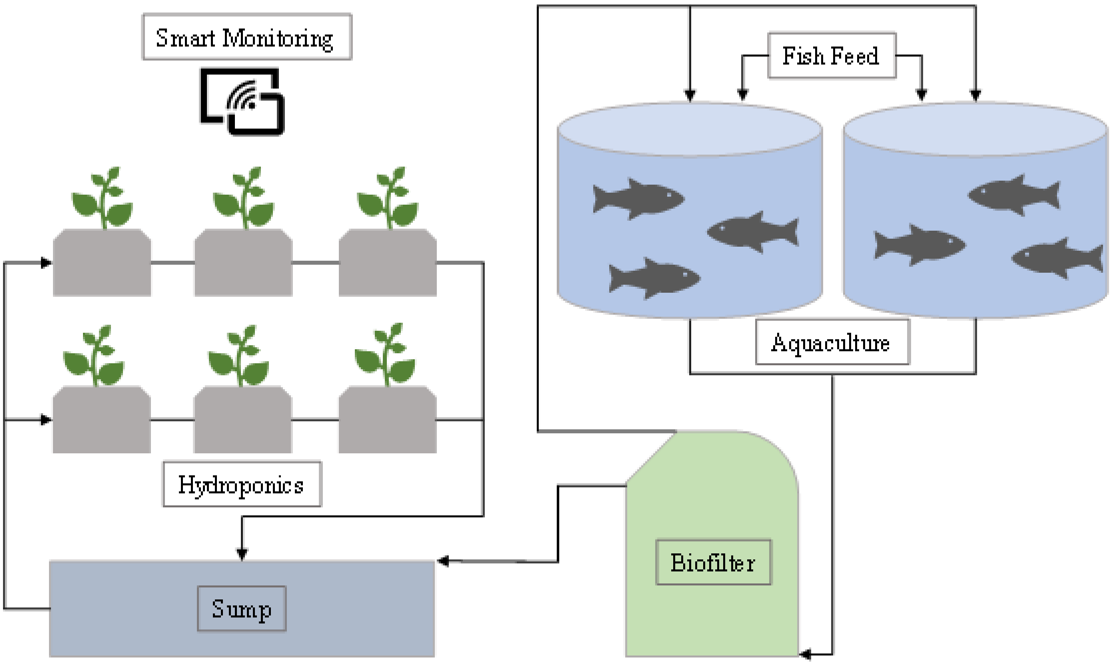

Figure 1-1. Representation of smart decoupled aquaponics system with NFT grow beds

1.3.1. Primary Advantages of Aquaponics

One of the main advantages of an aquaponics system is water efficiency. The nitrate-rich water flows through the grow channels and gets accumulated in the sump before being fed in the fish tank again, thus creating a closed-loop water-efficient system. This traditional approach is referred to as a closed-loop or coupled aquaponics system and often requires compromises between aquaculture and hydroponics in terms of pH, temperature, and nutrient concentration [21]. These challenges are addressed by the decoupled aquaponics system in which the two subsystems are separated and individually optimized. Compared to the traditional farming system, where an estimated 10% of water gets absorbed by the plants and the remaining is lost to evaporation and overflow [22], aquaponics can be considered a high water-efficient system. As summarized by [23], aquaponics typically wastes 0.3% to 5% of the system water, mainly in plant transpiration, evaporation losses, scheduled maintenance operations, and fish splashes. Furthermore, aquaponic systems can be installed in densely populated areas, which often witness high food demands, thus reducing the transportation costs and other aspects related to supply chain management [24].

Industry 4.0 has significantly impacted modern agriculture, with smart farming systems becoming more efficient and automatized. The implementation of digital twins that mirror physical entities of automated plant production lines in the virtual world has improved the system's performance [25]. Monitoring and control of aquaponics have become possible by integrating the internet of things (IoT) concept, utilizing various sensors and network protocols to gather real-time data regarding important crop, aquatic, and environmental parameters [26]. For instance, energy monitoring systems that capture the energy consumption per unit yield have been devised, thus enhancing the efficiency of the process [27]. Learning factories combining transdisciplinary engineering problems with smart aquaponics have been established to present an effective environment for skills and knowledge development [28].

1.3.2. Impediments to Large-Scale Aquaponics Implementation

Despite all the advantages of this imminent and growing technology, a few challenges need special attention, especially when considering its large-scale implementation. There is a significant interdependence among various components within an aquaponic system. A delicate balance must be established among the important parameters for the system to be functional and efficient [29]. It is of paramount importance to ensure that nominal conditions are met for the growth and development of all three varieties of organisms that are present in the system - fish, bacteria, and plants. Some important parameters that need to be constantly monitored and recorded include water quality, pH levels, air humidity, water and atmospheric temperature, dissolved oxygen levels, or luminance [30].

Aquaponics in rural and peri-urban contexts perform differently than ones in urban conditions, primarily due to economic viability, environmental sustainability, and level of technical and environmental control [20]. Touted as a land-efficient production system, aquaponics offers advantages in land-scarce urban regions with high property costs and far greater population density that perpetually witness high food demands. Operating aquaponics facilities in such regions may reduce the transportation cost and other aspects related to supply chain management [24]. On the other hand, rural and peri-urban regions with comparatively low land prices that lack any site-specific superiority, such as renewable energy sources, waste energy supply, etc., offer inadequate incentives for setting up such energy-intensive agricultural units [31].

1.4 Research objectives

The research objectives for this thesis are derived from studying the aquaponics system, its benefits and drawbacks, and impediments to the large-scale implementation of this technology in commercial facilities. The main research objective is to:

"Develop an ontology-assisted framework that assists in designing, selecting, and implementing the hydroponic component and artificial illuminance for indoor aquaponics system and further optimize the energy-use efficiency of Lactuca sativa L. (Little Gem) hydroponic plantation within the aquaponics facility."

To optimize the energy-use efficiency and develop an ontology framework, the **objectives (Os)** of this study are subdivided into the following actions:

O1. Review the current research on energy-efficient indoor aquaponics practice and identify key energy consumption areas through systematic literature analysis and mapping.

O2. Adapt the existing aquaponics ontology knowledge model to include relevant information related to energy and resource consumption.

O3. Develop an interactive graphical user interface for education and training, with data populated from the new ontology model. Provide a step-by-step guide on developing the energy-efficient aquaponics system.

O4. Employing knowledge from the ontology model, compare the energy-use efficiency for lettuce plantation under nutrient film technique and deep-water culture hydroponic systems within the aquaponic facility.

O5. Based on the results from the fourth objective, evaluate the energy-use efficiency for lettuce plantation under nutrient film technique hydroponic system using pulsed and continuous LED artificial illuminance, facilitating the design, selection, and implementation of a hydroponic component of aquaponics facility.

The research has fulfilled the objectives outlined above and has recorded the results from various experiments in the aquaponics ontology model – an ongoing effort to arrange knowledge pertaining to aquaponics. This ontology model can be incorporated by commercial facilities and aquaponics practitioners alike to ensure energy-efficient operation.

1.5 Thesis Structure

The thesis layout is represented in a pictorial form in Figure 1-2. This thesis comprises of five chapters. Chapter 1 presents a brief introduction to research motivation and sustainable food production systems with special emphasis on aquaponics – advantages, and limitations. This chapter also frames the research objectives of this thesis. Chapter 2 presents the systematic literature analysis, "Review on Energy Efficient Artificial Illumination in Aquaponics," addressing the first research objective. Chapter 3 fulfills the second and third research objectives by highlighting the "Ontology-based Interactive Learning Approach for Transdisciplinary Teaching in Learning Factories." Chapter 4 is subdivided into two parts. The first section covers "Comparison of Energy-use Efficiency of Lettuce Plantation under Nutrient Film Technique and Deep-Water Culture Hydroponic Systems," an article that addresses the fourth objective. The second part of this chapter presents an article, "Comparison of Energy-use Efficiency for Lettuce Plantation under Continuous and Pulsed Artificial Illuminance using Nutrient Film Technique Hydroponic System," focusing on the fifth research objective. Finally, the conclusion of this thesis, summary of research contributions, limitations of this study, and future work directions have been discussed in Chapter 5.

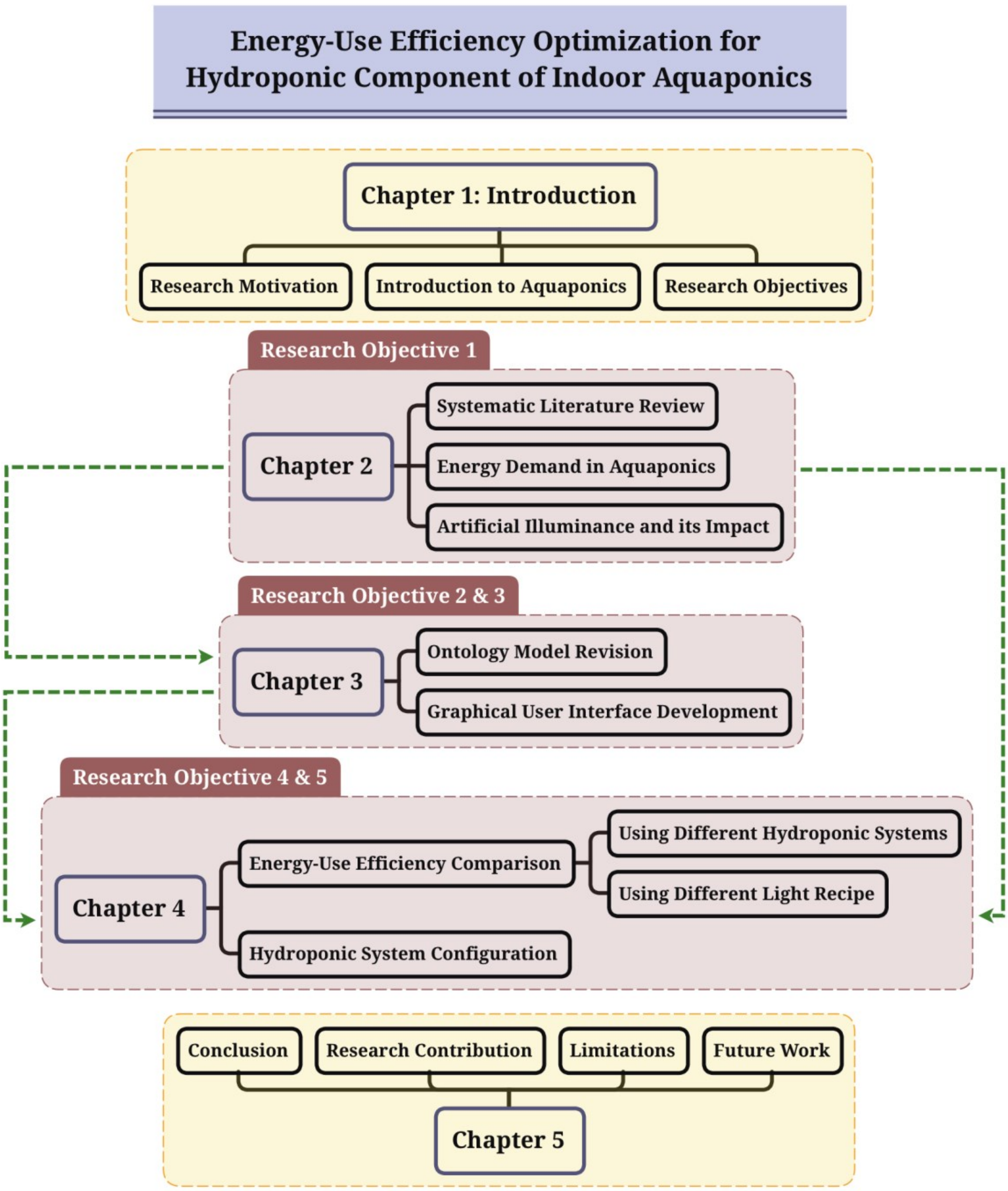

Figure 1-2. Pictorial representation of thesis layout

Chapter 2 Literature Review on Energy Efficient Artificial Illumination in Aquaponics

2.1. Introduction

The world population is facing an unprecedented increase and with that arises the need for additional agricultural resources [1]. This increase has put a tremendous amount of pressure on modern society to develop ingenious sustainable food production systems. Aquaponics, an emerging alternative to traditional farming practice, promises to offer a sustainable and efficient solution to this problem, though its economic viability is still being tested [32]. The recent shift towards Industry 4.0 technologies, such as the internet of things, big data, artificial intelligence, or cloud computing, has opened new avenues for this farming method to enhance productivity, energy efficiency, and yields while enabling smart management decision-making [33], [34]. However, the implementation of a large-scale aquaponics system faces multiple challenges, both from the technical and economic aspects, one of which is related to excessive energy consumption. Up to three-quarters of this energy is consumed by illumination [14], [35], [36]; as such, the detailed focus of this chapter has been placed on the growth lights - types, specific wavelengths, photoperiod, daily light integral, and switching frequency. This chapter follows a systematic approach to review the current literature on energy efficiency in aquaponics and address research questions about these topics. Furthermore, smart monitoring applications that enhance energy-use efficiency and use various emerging technologies such as big data and the internet of things have been discussed.

2.2. Aquaponics Review

Studies in the domain of aquaponics have seen a significant rise over the past few years, with researchers focusing on various diverse topics such as types of aquaponic systems

[37], hydroponic components [38], [39], variety of species [40]–[42], management practices [19], [23], [43]–[45], environmental considerations [46]–[48] and energy efficiency [49], [50]. However, a complex system such as aquaponics involves multiple disciplines ranging from agriculture, aquaculture, microbiology, horticulture, chemistry, mechanics, and mechatronics, making a comprehensive review on aquaponics a daunting task. Few literature reviews [51], [52] have tried to provide a holistic summary of aquaponics in general. However, they appear inadequate in expounding the energy use efficiency (EUE) of aquaponics – or in other words, the ratio of biomass produced to the energy consumed. In an attempt to identify the energy demand and sink for greenhouse aquaponics facilities, a recent study highlights electricity as the dominant contributor to all environmental impact categories [35]. The result from this study is featured in Figure 2-1. However, indoor growing spaces rely exclusively on artificial illuminance and require less insulation when compared to greenhouses, and as such, consume a higher portion of electricity for lighting [20]. Artificial illuminance alone accounts for an estimated 65% of the total energy consumed by indoor aquaponics [36], [53]. Furthermore, artificial lighting, which provides the energy required to carry out photosynthesis - a photochemical reaction occurring within plant cells converting atmospheric CO2 to carbohydrate, contributes to 20-30% of the total production cost associated with indoor farming [54]. As such, numerous reports on specific concepts related to energy efficiencies, such as the efficiency of various lighting sources [55], the effect of photoperiod and daily light integrals [56], LED red:blue wavelength ratio [57], and switching frequency [58], have been published in the past, however, existing literature does not address the light response spectrum for specific plants at different growth stages conclusively. Some studies have tried to address these challenges in an analytical manner, yet there appears

to be a need to present a more holistic approach toward artificial illuminance energy management of large-scale aquaponics and provide a literature review on this particular topic of interest. This chapter attempts to unite these findings and draw relevant conclusions regarding the energy use efficiency that is essential for the longevity, economics, and sustainability of aquaponics.

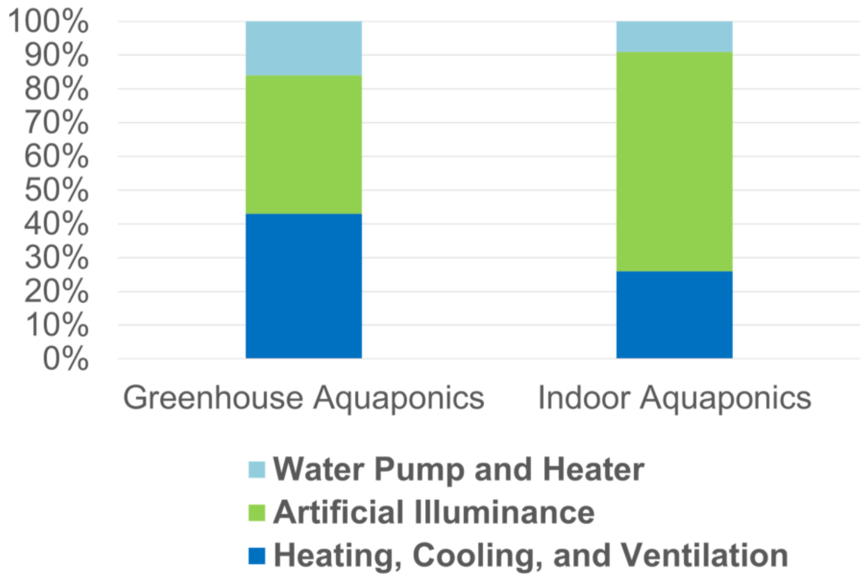

Figure 2-1. Energy demand and sink for greenhouse and indoor aquaponic system [14], [35]

2.3. Research Methodology

The methodology used to conduct a systematic literature review can be broadly classified into two steps: 1) defining the review protocol and 2) performing the evaluation process. These steps have been elucidated in the sequential subsections to follow.

2.3.1. Review Protocol

A review protocol provides a concise strategy to be used in the literature review. As such, this chapter follows the preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach that aims at identifying, filtering, and critically evaluating the relevant literature to answer certain research questions. Being a powerful technique, this systematic review is an attempt to unify the perspective and results from various empirical findings.

2.3.1.1. Research Questions

This systematic review adheres to a clearly defined protocol and attempts to answer a set of research questions. Ranging across a multitude of dimensions, these research questions are devised to get insights into artificial illuminance energy-use efficiency in the aquaponics system. The following list presents the seven research questions addressed in this literature review:

1. Which lighting technology has been found to be energy efficient for aquaponics?
2. How does a specific wavelength promote the growth and development of plants whilst minimizing energy consumption?
3. What is the optimum daily light integral or photosynthetic photon flux density that induces enhanced crop yield?
4. How does the artificial light switching frequency impact the energy-use efficiency of different plant species?
5. What is the correlation between resource use efficiency (RUE) and energy in aquaponics?
6. How have the recent developments in IoT and automation impacted the energy-use efficiency of aquaponics?
7. What are the future search directions and open perspectives of energy-efficient aquaponics in terms of its large-scale implementation to establish a sustainable food production system?

2.3.1.2. Literature Search and Selection Criteria

After establishing the research questions, an approach needs to be formulated to identify the relevant literature. For the purpose of this review, the literature sources focus on two online publication repositories: Scopus and IEEE Xplore. A preliminary search equation consisting of ideas and concepts directly related to energy use efficiency in aquaponics is outlined.

Preliminary search equation: (energy AND efficiency) AND (aquaponics OR (vertical AND farming)).

Based on this search equation, a total of 2,804 results were obtained (Scopus - 2,654 and IEEE Xplore - 150). The evolution over the recent years of the number of publications obtained through the preliminary search equation is illustrated in Figure 2-2, depicting the recent surge in the number of publications in the field of energy efficiency for vertical farming and aquaponics. This calls for a more systematic review of the recent literature to coalesce the outlook and present a comprehensive dissertation.

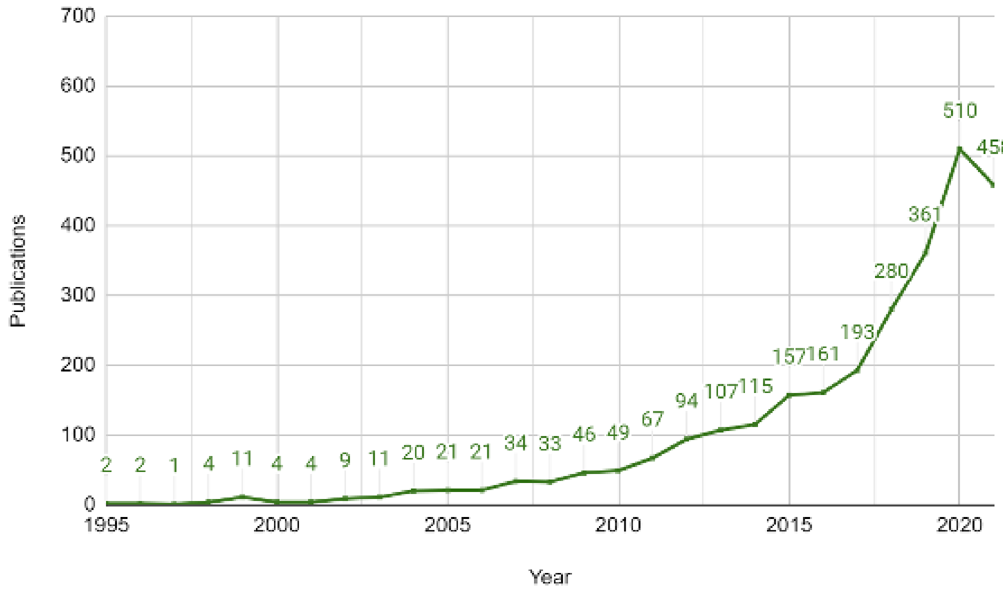

Figure 2-2. Yearly publication rate obtained from the initial search equation.

Literature searches often yield many results that might not be relevant to the current review or fail to answer the research questions. Thus, a strategy is developed that identifies the pertinent literature and evaluates it based on certain predefined criteria.

<u>Inclusion Criteria:</u>

- Peer-reviewed journal articles and conference papers.
- Studies published during the period between 2011 to 2021.
- Studies that provide answers to the research questions.
- The articles must include the title, year of publication, source, abstract, and DOI.

<u>Exclusion Criteria:</u>

- Summaries of events and seminars, book reviews, and editorials.
- Papers referring to energy efficiency but not applicable to aquaponics, hydroponics, or vertical farming.
- Papers published before 2011.
- Publications that are not in English.
- Publications that are not available in open access.

On the basis of the above criteria, the preliminary search equation is modified such that more relevant and up-to-date literature is obtained.

Final search equation: (energy AND efficiency) AND (aquaponics OR (vertical AND farming)) AND (LIMIT-TO (OA, “all”) AND LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011)) AND LIMIT-TO (LANGUAGE, “English”)).

This final search equation yields a total of 1,012 records (Scopus - 885 and IEEE Xplore - 127) that will be carried forward to the evaluation process.

2.3.2. Evaluation Process

Once the review protocol is defined, the next step in the systematic analysis is to start the evaluation process. An evidence-based approach, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis), is used for this purpose, as expounded in Figure 2-3 [59]. This approach maps out the number of records identified, screened, checked for eligibility, and eventually included in the systematic review, as expounded below:

- Identification: Literature review requires exploring different databases, which at times results in duplicate records. These duplicates need to be identified and consequently eliminated from the systematic review. After conducting the initial search, 885 records from Scopus and 127 records from IEEE Xplore were obtained.
- Screening: This step involves manual filtering based on the title and abstract before reading the full article and making the final eligibility decision. Guided by the review questions to be answered, a total of 551 records are excluded based on title screening, followed by another 208 records based on abstract screening.
- Eligibility: After the initial articles were screened, a total of 238 records are assessed for eligibility by performing a thorough read of the full text. Out of these, 186 articles were excluded from the systematic review, as they either failed to answer the research questions, or the full text was not available.

- Inclusion: After identifying a total of 56 eligible articles from the two databases, additional cross-references pertaining to the discussion are also incorporated in the study, adding up the total number of publications for meta-analysis to 77.

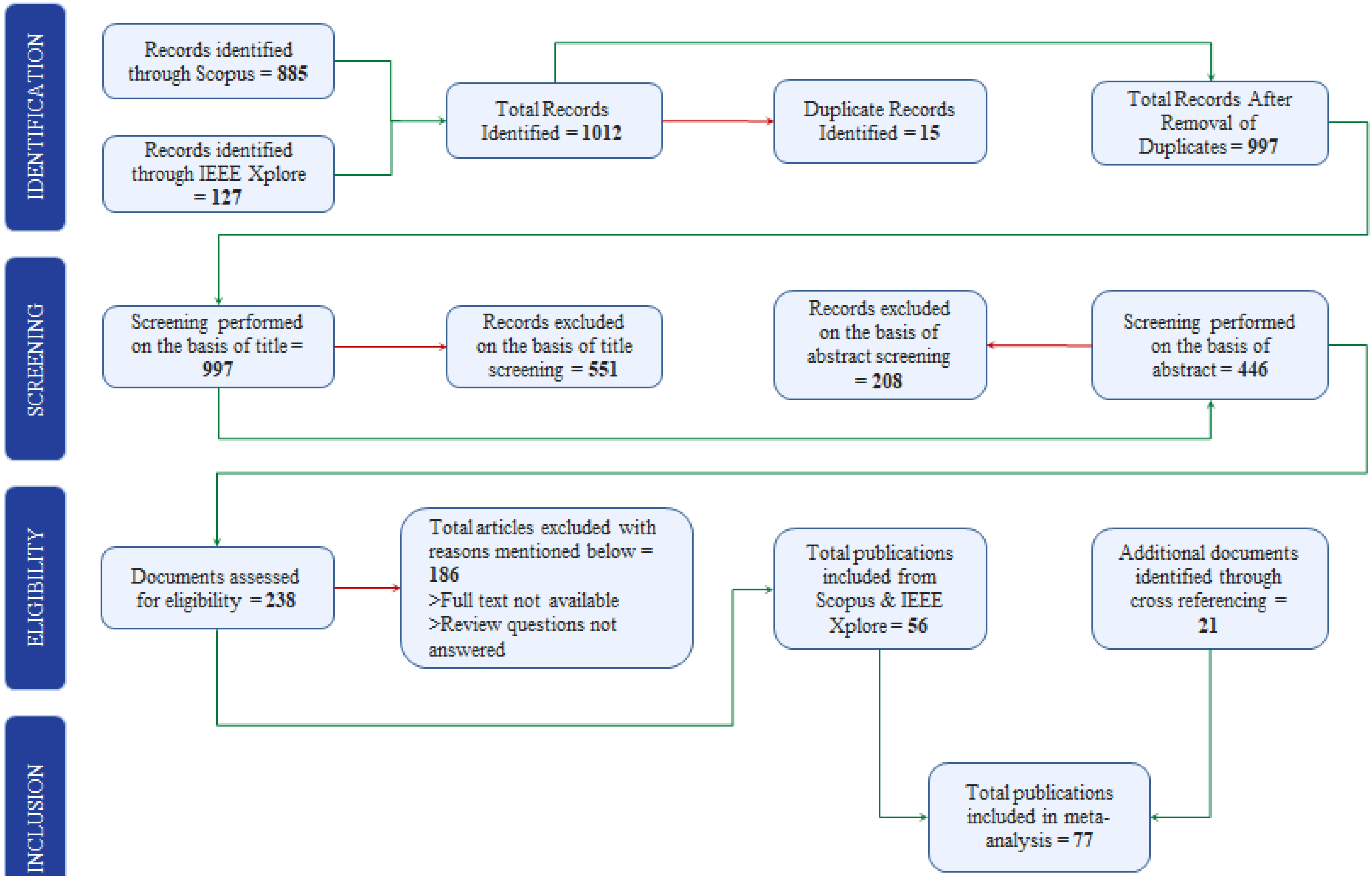

Figure 2-3. PRISMA approach for record identification.

2.4. Results

The systematic literature review yields articles from multiple disciplines, as shown in Figure 2-4, with the majority of articles belonging to the energy (20.8%) and engineering (19.5%) domains. 16.9% and 14.7% of the reported articles are associated with environmental sciences and agriculture & biological sciences, respectively. This inclusion of a variety of subject areas provides insights from disparate fields and thus helps in achieving a comprehensive summary of the recent trends related to energy-use efficiency in aquaponics.

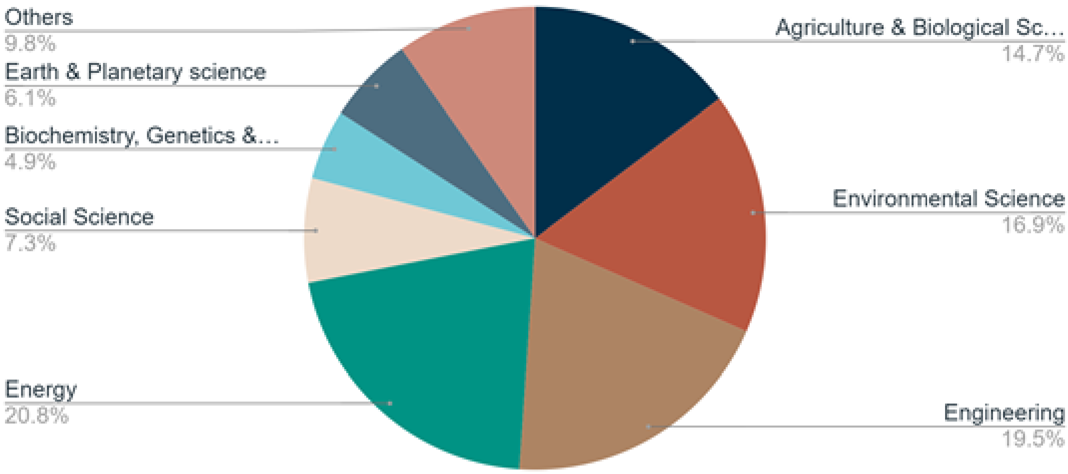

Figure 2-4. Classification of literature retrieved based on subject area.

Although the majority (31%) of papers are retrieved from a mix of various reputed journals such as *Applied Energy*, or *Science of the Total Environment*, a significant portion (21%) of reports is obtained from the *Journal of Cleaner Production*, enhancing the credibility of qualitative research and systematic review. A visualization of the publications' distribution in journals is presented in Figure 2-5.

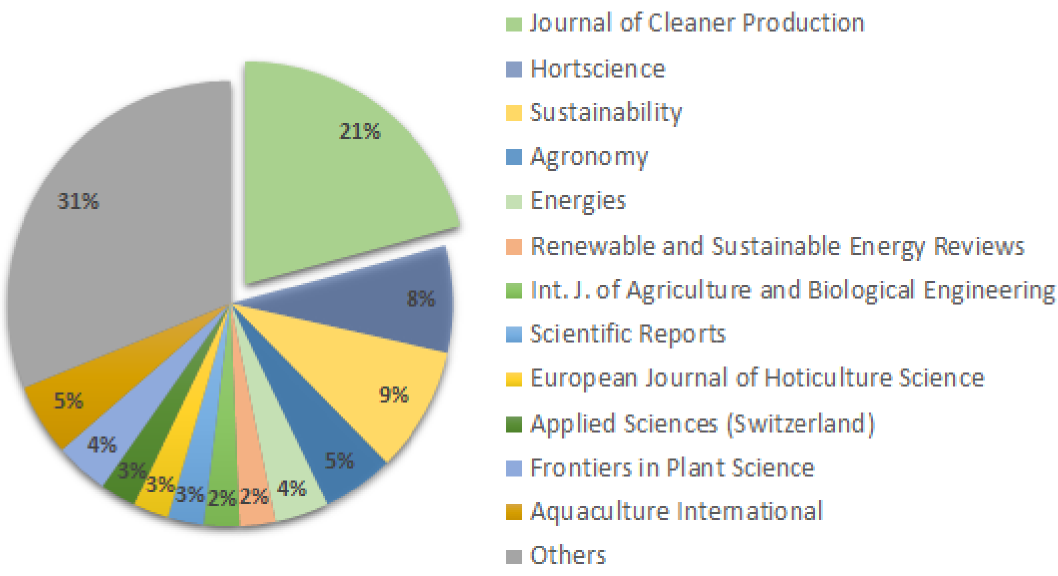

Figure 2-5. Classification of literature retrieved based on the journal where it is published.

The major trends that became apparent after conducting the systematic literature review on energy use efficiency in aquaponics are observed in topics such as artificial lighting sources used for plant illumination, photoperiod, daily light integrals, source wavelength, the ratio of red:blue light (R:B), switching frequency, and monochromatic lighting sources. These have been elucidated in the sequential sections to follow.

2.4.1. Artificial Lighting

Lighting is an essential component of the aquaponics system, providing plants with the much-needed energy for carrying out the photosynthesis process - a photochemical reaction occurring within the plant cells, converting atmospheric CO2 to carbohydrates. Plant photoreceptors absorb the incoming radiation and are responsible for growth, morphology, and photosynthetic efficiency [35]. Over the past few years, several artificial lighting sources have been deployed in indoor hydroponic settings, such as high-intensity discharge lamps (HID), induction lighting (IND), fluorescent lamps (FLO), and light-emitting diodes (LED). Operating on different working principles, these lighting sources offer varying energy efficiency and, in turn, induce distinct plant growth rates. This section attempts to answer the first question of the systematic review and analyses different artificial lighting solutions used for aquaponics.

A study comparing four different artificial lighting sources for aquaponics recorded a significantly higher average weight for swiss chard and kale grown under LED lighting, offering higher plant production per unit energy consumption compared to FLO, IND, and HID [24]. Furthermore, the type of artificial light chosen for the system did not affect plant health, which was inferred by the plant root-to-shoot ratio. Based on the data gathered by Paucek et al., efficacy values of 2-3 μmol/J (70%) were reported for most LEDs in controlled and closed plant-growing environments suggesting an overall better performance [60]. This result is coherent with another study that recorded 75% energy savings associated with LEDs lighting compared to a greenhouse with high-intensity discharge lights, while both systems have similar yields [61]. Furthermore, the nutrient and chlorophyll content did not differ significantly with the choice of lighting. Martineau et al. concluded that though higher energy consumption is associated with LEDs, the growth rate is significantly enhanced, thus generating higher plant yield per unit energy [55]. In a separate study, LED systems showed more energy efficiency, with approximately 17% savings when compared to traditional fluorescent lighting [62]. Figure 2-6 illustrates the steep average growth rate (in $g/m^2/kwh$) associated with different light sources during the growth of swiss chard and beta vulgaris.

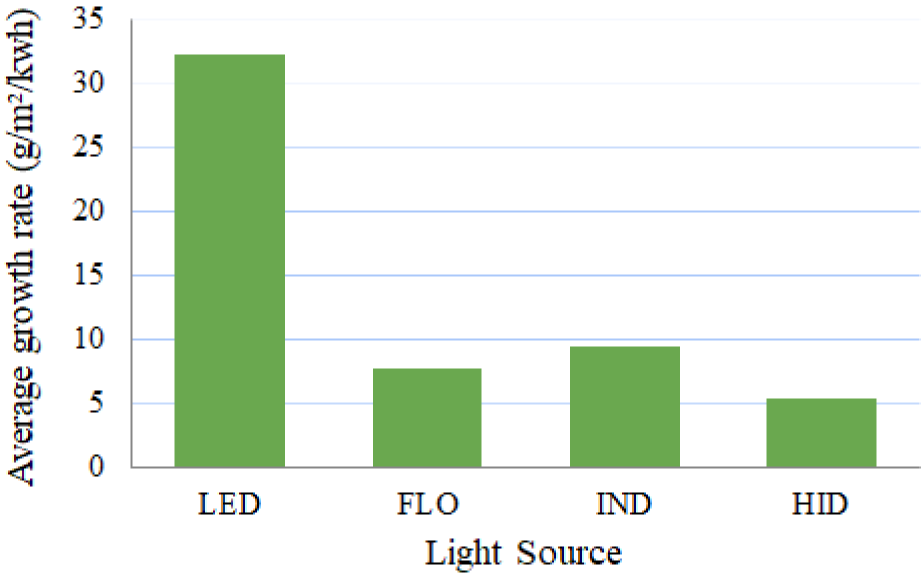

Figure 2-6. Average growth rate (g/m²/kwh) for swiss chard and beta vulgaris grown under four artificial lighting conditions [24]

Kikuchi et al. attributed the lower life-cycle greenhouse gas (LC-GHG) emission of plant factories to LED illumination. Compared to FLO, LEDs' long life and lower power consumption result in reduced LC-GHG [49]. A separate study concluded that due to their compact design, lower surface temperature, enhanced efficiency, and a broad wavelength spectrum, LEDs attract great attention among researchers and developers of plant factories as the principal source of artificial lighting [53].

2.4.2. Photosynthetically Active Radiations (PAR)

Photosynthetically active radiation (PAR) is a spectrum of light that plants require to grow and develop. It includes light in the 400-700 nm wavelength range, where the light-absorbing photosynthetic pigments use the energy for photosynthesis. Under natural sunlight illumination, the plant receives the entire spectrum of visible radiations resulting in enhanced growth rate and plant quality [63]. However, the intricacy of large-scale aquaponics requires close environmental control, thus, calls for artificial lighting sources to provide the necessary PAR. Singh et al. reported that most of the light sources convert 30% of the energy into usable light for plant growth and development. However, LEDs tend to have about 50% conversion rate, generating more frequency in PAR, which leads to enhanced plant growth when compared to the other lighting sources [61]. Similar results were obtained by Yan et al. while examining the effect of LED lights with different spectral frequencies on the growth of green and purple leaf lettuce cultivars [64]. Another study tried to quantify the illumination requirements for plant growth by considering the conversion efficiency of electricity to PAR and concluded that LEDs could be adjusted to plants' demand, substantially reducing energy costs [65]. Addressing the second and third research questions, the impact of wavelength and different light treatments has been discussed in detail in the subsections to follow.

2.4.2.1.Effects of Light Wavelength

Being selective in absorbing incident radiation, plants tend to soak up wavelengths based on their specific requirement. Photosynthetic pigments, mainly chlorophylls (chlorophyll a and chlorophyll b) and antenna pigments (carotenoids, lycopene, or lutein), partake in specific wavelength absorption and thus are critical for photosynthesis [55]. As an example, the absorption per wavelength by chlorophyll a and chlorophyll b has been illustrated in Figure 2-7. Singh et al. studied the response of specific wavelengths to plant development and inferred that the emission of wavelengths tailored for a specific growth phase could lead to better performance in the germination, growth, and flowering period, as expounded in Table 2-1 [61]. Gomez et al. further added that targeted photomorphogenic, biochemical, or physiological responses could be induced by choosing specific LED wavelengths [66].

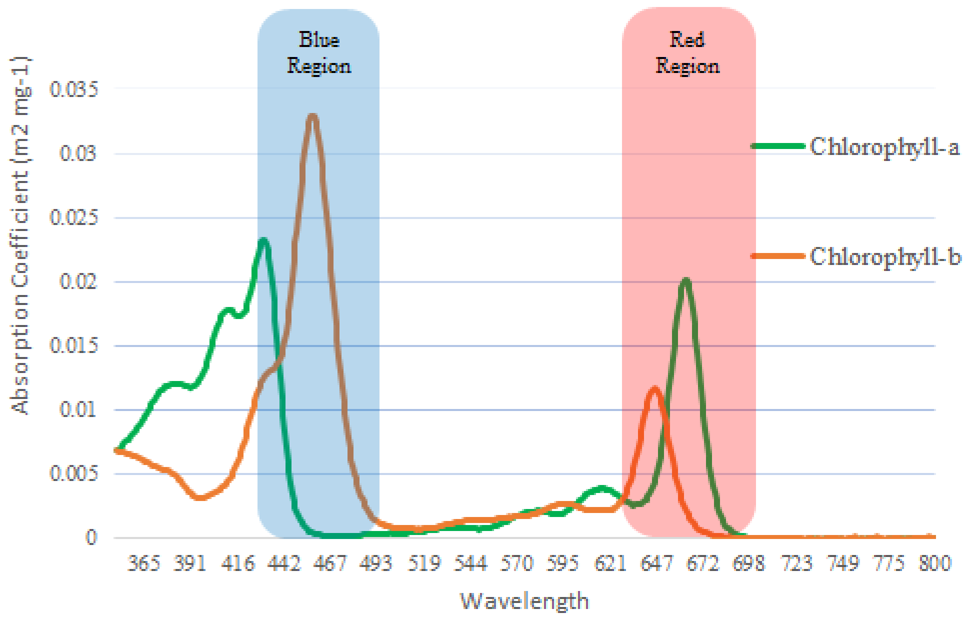

Figure 2-7. Absorption of Chlorophyll a and b for different wavelength (Adapted from [67])

Table 2-1. Impact of varying wavelengths on plants

Wavelength (nm)	**Region**	**Impact on plants**
200 - 280	ultraviolet C	Highly toxic and harmful to plants
280 - 315	ultraviolet B	Loss of color - fading
315 - 380	ultraviolet A	Does not affect the plant growth
380 - 400	ultraviolet A / visible light	Moderate light absorption by pigments - Beginning of photosynthesis
400 - 520	visible light	Peak absorption by chlorophyll - Strong impact on plant development
520 - 610	visible light	Significantly less absorption by pigments - Low impact on plant development

610 - 720	visible light	Large absorption occurs - Strong influence on growth, flowering and budding
720 - 1000	far-red / infrared	Little to no absorption - Flowering and germination still impacted
> 1000 nm	infrared	Absorptions converted to heat

2.4.2.2.Impact of Tailored LED Treatment

In the recent literature, authors have focused on tailored LED treatments to obtain desired yield and nutritional characteristics for wide variety of plants. Apart from providing high energy efficiency, these LED treatments can induce a greater net photosynthetic rate, higher vitamin C contents, lower nitrate content, and oxalate accumulation reduction [68]. Yan et al. observed an approximately 30% increase in the lettuce leaf fresh and dry weight on the application of far-red light in red plus blue LEDs, concluding that white plus red LEDs are better, or on par with white plus blue LEDs [57]. Similar results were obtained by Jin et al. while studying the significance of plant density and far-red inclusion on the growth of lettuce, concluding that PAR, which is responsible for orchestrating the photosynthesis process in plants, supplemented with far-red radiation (700-800 nm), resulted in stem elongation along with leaf expansion leading to better light interception [69]. A separate study measuring the spectral quality of artificial light found a positive correlation between higher red:blue (R:B) ratio and energy-use efficiency, concluding that higher R:B ratio and relatively higher PER (photon efficiency of red light) are quintessential in order to increase the energy-use efficiency in indoor lettuce plantations [70]. Table 2-2 summarizes research conducted on a variety of plant species to study the impact of tailored LED treatments.

Table 2-2. Effect of different LED treatments on a variety of plant species.

Reference	Plant Species	Light Treatment	Effect
[57]	Green and purple leaf lettuces *(Lactuca sativa L. cv. Lvdie and Ziya)*	Application of far-red light in red plus blue LEDs	Approximately 30% increase in the lettuce leaf fresh and dry weight.
[68]	Spinach *(Spinacia oleracea L.)*	LED with R:B ratio of 1.2	Higher fresh and dry spinach weight, energy yield, and light-use efficiency.
[71]	Tomato *(Solanum lycopersicum)*	LED with R:B ratio of 2.3	39% increase in dry mass and better growing efficacy than fluorescent treatment.
[72]	Lettuce *(Lactuca sativa L.)*	LED with R:B ratio of 0.9	Highest biomass production efficiency with superior energy use efficiency (3.64%) and light use efficiency (1.20%).
[70]	Variety of lettuce *(Lactuca sativa L.)*	LED with R:B ratio of 4.47	Increased lettuce shoots, dry weight, and leaf expansion along with highest energy-use efficiency (EUE) obtained.
[73]	Four varieties of tomato cultivars *(Solanum lycopersicum)*	LED with R:B ratio of 1.5	Increase in plant growth, stem diameter, leaf area, and net chlorophyll content.

[74]	Basil *(Ocimum basilicum cv.)*	LED with R:B ratio of 3.0	Greater biomass yield generated along with improved plant chlorophyll content and enhanced mineral leaf concentration, resulting in better resource use efficiency and energy consumption per unit yield.
[64]	Lettuce *(Lactuca sativa L.)*	LED with R:B ratio of 2.7	Higher fresh leaf yield and improved light-use efficiency.

2.4.2.3. Daily Light Integral and Photosynthetic Photon Flux Density

Desirable plant growth at reduced energy consumption can be ensured by optimizing the artificial lighting environment. Taking this into consideration, the effect of daily light integral (DLI) and photosynthetic photon flux density (PPFD) on the growth, development, quality, and yield of plants has been studied in detail [64], [73]. Measured in moles of light per square meter per day, daily light integral (DLI) is the amount of photosynthetically active radiation (PAR) received by plants each day [75]. Analogous to DLI, photosynthetic photon flux density (PPFD) is defined as the amount of photosynthetically active photons that illuminate the plant area each second and is expressed in $\mu mol.m^{-2}.s^{-1}$ [76]. Another important parameter significantly effecting the energy-use efficiency in aquaponics is the photoperiod – amount of time each day during which plants receive illumination in the PAR region [61].

Zheng et al. observed a 38.9% increase in the number of strawberries *(Fragaria × ananassa)* runner plants as the DLI rose from 8.6 to 11.5 $mol.m^{-2}.d^{-1}$, while the biomass of runner plants and crown diameter showed identical results [56]. This study concluded that a daily light integral in the range of 11.5-17.3 $mol.m^{-2}.d^{-1}$ was ideal for improving the strawberry harvest and runner growth for indoor hydroponics system illuminated by LEDs, with 11.5 $mol.m^{-2}.d^{-1}$ provides the best energy yields. Similar results were obtained by Yan et al. for lettuce plantation as the experiment resulted in a higher fresh plant biomass and energy-use/light-use efficiency on the application of 12.6 $mol.m^{-2}.d^{-1}$ DLI [57]. Pennisi et al. concluded that an optimal management directive for indoor plantation of leafy vegetables and herbs is considered to be a 16 h/day photoperiod with a DLI of 14.4 $mol.m^{-2}.d^{-1}$ [77]. Further literature analysis was in coherence with the above results, with 48% of the studies recommending DLI in the range of 11.52 – 14.4 $mol.m^{-2}.d^{-1}$ as represented in Figure 2-8.

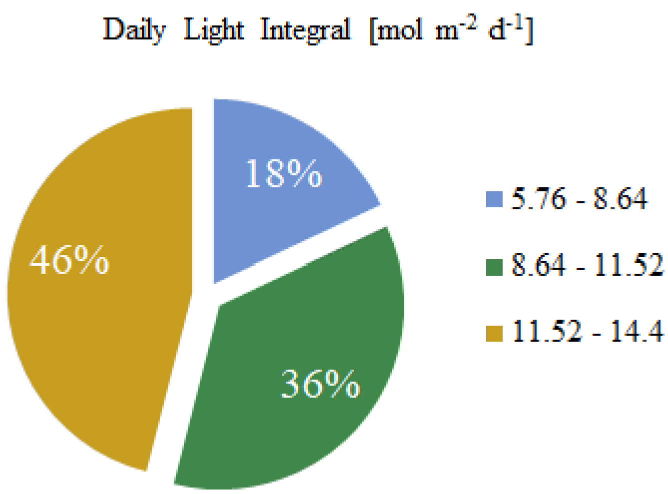

Figure 2-8. Recommended DLI range in $mol.m^{-2}.d^{-1}$ based on the various literature analyzed.

2.4.3. Switching Frequency

A plausible approach to enhancing EUE in aquaponics comes from replacing continuous lighting with a pulsed supply often modulated by the switching frequency – the rate at which light is turned on and off. This section expounds on the findings of various studies correlating the energy-use efficiency and artificial lighting switching frequency with the aim to answer the fourth research question.

The light spectrum of different wavelengths, called light recipes, can be configured in either continuous or pulsed mode and can offer significant energy savings [58]. Harun et al. suggested a possible strategy to enhance the energy-use efficiency of indoor farming to utilize pulsed or intermittent lighting instead of continuous lighting [78]. Intrigued by the results, Kanechi et al. studied the impact of pulsed light on the growth of lettuce and concluded that a 50% duty cycle resulted in significant energy savings without altering the plant's net chlorophyll content or quantum yield (ØPSII) [79]. Similar results were obtained by Song et al. while observing the seedling performance during the early photomorphogenic development of sprouts, kale, and beet [80]. This study concluded that approximately 30-50% energy efficiency could be attained by shorter light intervals of 10 seconds in a full 12-hour photoperiod treatment without affecting visible seedling traits. Olvera et al. modeled the LED energy consumption for closed plant production systems based on two artificial intelligent models, genetic programming (GP) and feedforward artificial neural network (FNN), and summarized that significant energy savings could be obtained by implementing pulsed LED lighting with low switching frequency without effecting the plant properties apart from the additional benefits of increased LED lifetime [81]. Further studies [82], [83] have validated the positive impact of pulsed LED treatment on the energy-use efficiency of indoor farming, as presented in Figure 2-9.

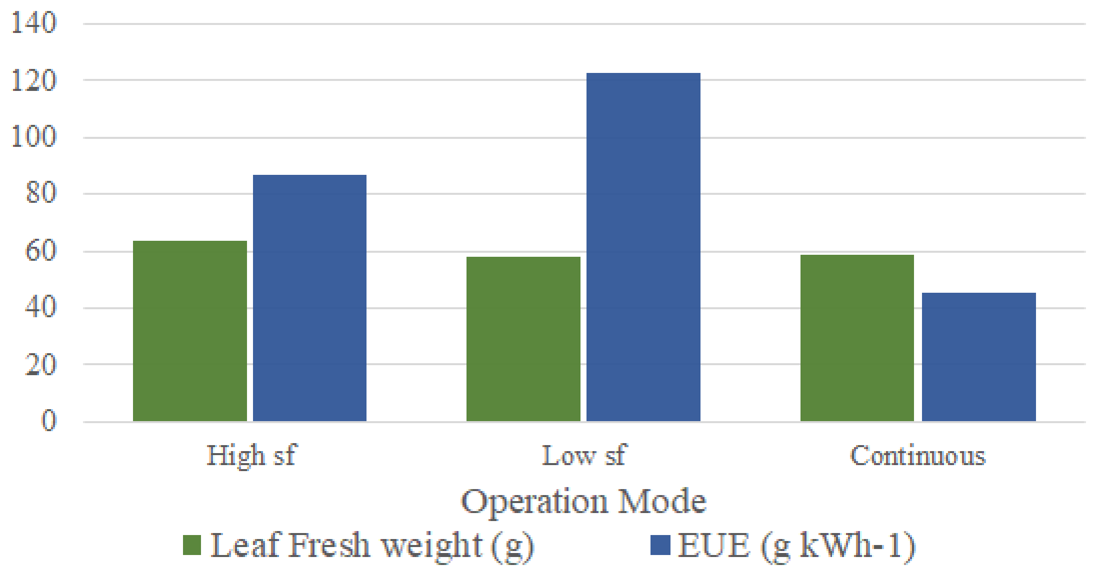

Figure 2-9. Leaf fresh weight and energy-use efficiency comparison for indoor lettuce plantation in pulsed (high and low switching frequency) and continuous mode [83]

2.4.4. Resource Use Efficiency

Artificial lighting is a key aspect in enhancing the EUE of aquaponics. However, for a system as complex as aquaponics, numerous avenues can help reduce the overall energy consumption, making the technology green and sustainable. This section attempts to address the relationship between resource use efficiency and energy consumption in aquaponics technology (fifth research question).

Urban agriculture relies on new plant production systems that offer minimal environmental impact or high resource use efficiency (RUE) - a ratio of utilized assets such as energy, water, or nutrients to the biomass generated [75]. A high resource-efficient system tends to offer energy-effective solutions, and thus recent studies have tried to address the RUE of aquaponics in an attempt to optimize the system for large-scale production [84], [85]. Dijkgraaf et al. modeled an innovative aquaponics system in Kenya and concluded that the aquaponics system's sustainability performance and energy-use efficiency greatly depended on the nutrient concentration range [86]. The results obtained from the study showed an optimized energy-efficient system with nitrogen nutrient use efficiency (NUE) of 77.74%, phosphorus NUE of 95.09%, and water use efficiency of 99.74%. Further studies are required to establish the in-depth relationship between RUE and energy efficiency in aquaponics.

Waste can be treated as a potential resource, and hence waste management can significantly enhance the sustainability of emerging technology. Aquaponics falls right in this bracket, as it relies on the wastes excreted by aquaculture to nurture and grow crops, making it a sustainable form of agriculture. Recent studies have tried to optimize waste management by exploring avenues to enhance energy-use efficiency. Thao et al. put forward an agro-based industrial zero-emissions system (AIZES) that reduces external energy demand by optimizing natural renewable energy sources and reducing the overall environmental load [87]. The study proposes that these benefits can be realized in aquaponics by incorporating biogas digesters and aquatic ponds that significantly enhance the resource use efficiency of the system. In a separate study, Zhu et al. recommend biogas production using aquaponics waste consisting of non-edible parts of plants and substandard yield, leading to enhanced nutrient use efficiency [88]. The author concludes that in addition to improving the economics of the process, a high RUE places a lesser energy burden on the aquaponics system.

2.4.5. Sensors, Smart Monitoring and IoT

Information is the primary source for decision-making, and smart agriculture relies on the use of information and communication technology [89]. It utilizes sensors and smart monitoring systems to gather data from heterogeneous sources such as IoT (internet of things) devices and makes use of big data and machine learning algorithms to predict various parameters related to plant growth rate, energy-use efficiency, light and resource use efficiency, or optimal harvesting time, eventually paving the way for precision farming [90]. Addressing an important question, the impact of IoT and automation on the energy efficiency of aquaponics has been highlighted in this section.

Wang et al. developed a module comprising of various sensors to wirelessly gather real-time data about various aquaponic variables such as light, water level, nutrients, and dissolved oxygen, which is later used to take data-driven and resource-efficient decisions [34]. Vernandhes et al. created a smart aquaponics system with a graphical user interface (GUI) to facilitate real-time monitoring and control, providing an energy-efficient solution by enabling the users to control the system remotely [91]. Urschel et al. describe a novel remote chlorophyll fluorescence (ChIF) sensor capable of gathering real-time physiological data for integration in the artificial lighting control system, thus augmenting the energy efficiency and providing enhanced crop growth. Crop relative growth rates (RGR), plant area (PA), leaf area ratio (LAR), and net assimilation rates (NAR) can also be predicted using the ChlF sensor[92].

In recent years, researchers have made efforts to develop smart systems capable of monitoring and controlling various parameters related to aquaponics, such as light intensity, temperature, resource utilization, energy consumption, relative humidity, electroconductivity, dissolved oxygen, and pH [27], [93], [94]. These decision-support prototypes are adept at predicting the real-time growth and resource-use efficiency and controlling it remotely, thus promoting the leap towards automation and enhanced energy efficiency in aquaponics technology [30], [95].

An architecture for a smart aquaponics system has been depicted in Figure 2-10. It comprises of various different sensors that capture data related to relative humidity, temperature, light intensity, energy consumption, water level, and plant growth rate [96]. This data is then transmitted using a network protocol to a cloud database at certain predefined intervals, based on the level of monitoring and control required by the aquaponics facility. A graphical user interface (GUI) designed to visually represent this data can allow the facility manager to monitor and control the real-time conditions of the system. Furthermore, the proposed system can generate alerts in case the parameters deviate from the control limit, enabling better crop quality and operation regulation. Predictive modelling algorithms can also be incorporated, enabling users to identify growth patterns, estimated time of harvest, estimated yield, and profit margins.

Apart from the various benefits of IoT and smart monitoring, it comes with its own set of demerits. The predominant one is the lack of IoT standards leading to less interoperability among systems. The initial cost of implementing the system and other security issues that may arise due to the absence of a proper encrypted network are some of the challenges that need to be addressed before implementing it in large-scale commercial aquaponics.

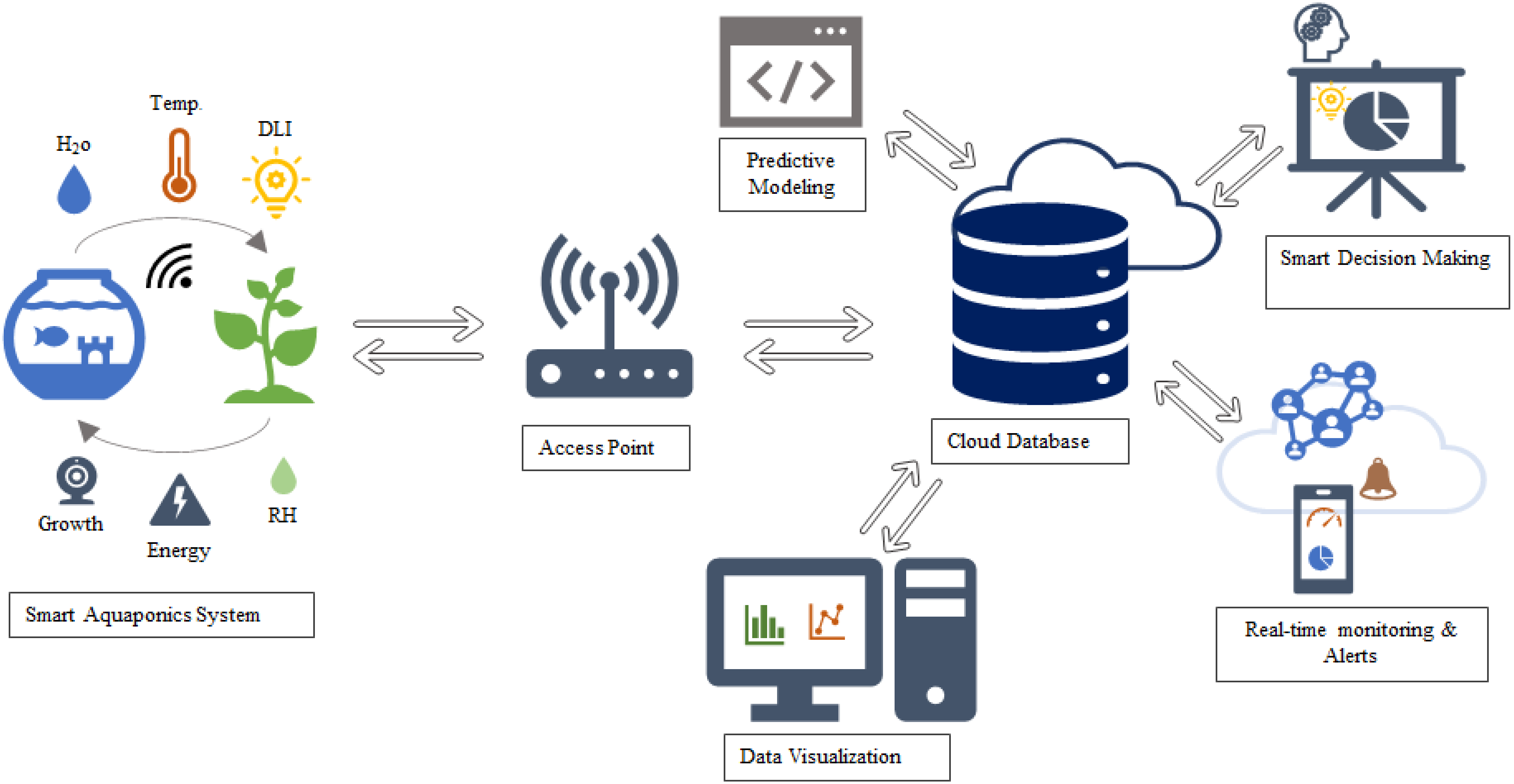

Figure 2-10. System architecture for smart aquaponics.

2.5. Discussion and Future Directions

Aquaponics promises to offer a resource-efficient alternative to conventional food practices. Apart from alleviating the pressure from traditional farming, it contributes to energy-efficient food production, less fertilizer/pesticide pollution, and less water wastage. However, the environmental benefits along with increased food security through the implementation of this technology can only be realized once this process gets commercialized extensively, paving the way for a profitable and energy-efficient food production business.

This literature review provides a basic understanding of various underlying factors affecting the artificial lighting energy consumption of aquaponics. The predominant element that influences the energy-use efficiency in full indoor aquaponic systems is the type of artificial lighting deployed for plant growth and development, with LEDs offering the highest biomass per kWh. Allowing total control over the spectral composition and light intensity, LEDs can be readily integrated into control systems resulting in better and enhanced plant growth. Another important parameter that affects energy use efficiency (EUE) is the wavelength and light treatment. Radiation spectrum tailored for specific growth phases and plant species can lead to better performance in the germination, growth, and flowering period, eventually increasing the photosynthetic efficiency while reducing the heat stress and flowering time. The impact of daily light integral and photosynthetic photon flux density on EUE is significant, with 46% of the studies recommending DLI in the range of 200 – 250 $\mu mol.m^{-2}.s^{-1}$ for an optimal yield to energy ratio. Furthermore, most of the authors recommended a photoperiod of 16 hours to provide the recommended PAR for carrying out photosynthesis in an energy-efficient manner.

Answering the final research question pertaining the future search directions and open perspectives, the opportunities presented by the relatively unchartered field of energy-efficient aquaponics can be realized by introducing resource-efficient systems, apart from promoting various digital initiatives. Enhanced resource use efficiency, especially with regard to waste management, may have a significant influence on the EUE of aquaponics. From the sustainability point of view, a food production system capable of harnessing energy from waste and utilizing the same to power the process can drastically reduce the energy load of traditional agricultural practices, leading to a lesser environmental burden, promoting circular economy within aquaponics while mitigating food insecurity across the world. Furthermore, large-scale aquaponics industries can leverage smart monitoring and big data analytics along with a decision-support framework to predict and model the energy-use efficiency for a wide variety of plants and fish at different growth stages. Various important parameters may be recorded and analyzed, based on which system can make smart decisions. With the inclusion of these automated systems, the need for manual intervention and inspection can be eliminated, allowing for a resource and energy-efficient operation.

Several challenges associated with the implementation of smart monitoring and big data in large-scale energy-efficient aquaponics still prevail, some on the organizational level, while others on the practicality of the application. Organizational challenges relate to the capex investments, manpower recruitment, setting up a technical team, and other management changes. On the other hand, the technical challenges typically involve sensor installation, internet connectivity, communication infrastructure, data transferring and storing, among others. These obstacles can be overcome by establishing aquaponics learning factories that educate, train, and provide opportunities for research and development whilst also providing a systematic integration between large-scale commercial systems and smart sensing or IoT systems [97]. Furthermore, raising awareness about the merits of smart aquaponics and pushing for government initiatives, policies, grants, and endowments to businesses venturing into this domain can significantly benefit this technology and the world food crisis in general.

2.6. Conclusion

Increasing contributions in the field of energy-efficient aquaponics are attracting attention from researchers and practitioners, primarily due to its potential of offering a sustainable food production system for the growing world population. This chapter is an effort to analyze and review the energy efficiency in the illumination of plant growing compartments in aquaponics. Various research papers have been analyzed and compared based on the artificial lighting technology, wavelength, light treatment, daily light integral, photoperiod, switching frequency, and overall performance of the system. An attempt has been made to answer various research questions pertaining to artificial lighting used in aquaponics. It is concluded that LEDs offer significant advantages over other existent alternatives, such as 75% higher EUE, about 50% light conversion rate, reduced operational costs, and long-lasting service period while at the same time providing robustness in tailoring specific light treatments for different plant species and growth phases. Artificial light DLI in the range of 11.52 – 14.4 $mol.m^{-2}.d^{-1}$ is found to be optimum for enhanced lettuce growth, while a high switching frequency is found to offer about 50% energy savings as compared to a continuous operation mode. The paper also discusses the emerging trends of improving the energy efficiency of aquaponics with smart monitoring and big data. Aquaponics learning factories that can bridge large-scale commercial units with energy-efficient, smart robust systems and help strengthen sustainability aspect of this technology have also been advocated.

Chapter 3 Ontology-Based Graphical User Interface for Aquaponics Learning Factory

3.1. Introduction

Interactive user interface provides a pedagogical approach to acquiring skills and developing knowledge regarding transdisciplinary areas, especially in the burgeoning engineering sciences domain. In fact, learning factories have been shown to provide the appropriate environment for transdisciplinary teaching. As an example, the AllFactory at the University of Alberta is a unique facility that encompasses agricultural and biological sciences along with industry 4.0 technologies. Aquaponics 4.0 mediates the growth of various plant and fish species while using engineering concepts to control the environment, minimize energy consumption, and ensure maximum quality control and high throughput. This chapter proposes a graphical user interface to provide a step-by-step guide on choosing the energy-efficient hydroponic and aquaculture component to investigate Aquaponics 4.0 systems, where all the required knowledge is extracted from an ontology model.

In this case, the use of the ontology model that stores the relevant foreign knowledge and is continuously accessed by the user through the interactive platform is researched. Offering interoperability of information across domains, ontology is defined as an explicit and formal specification of a conceptualization [98], [99]. This approach aims to visually present the desired knowledge to the user in an open and exploratory manner, enhancing and improving the user experience. The transdisciplinary environment used for the interactive platform is based on the AllFactory situated at the University of Alberta, Canada, which focuses on advanced digital manufacturing processes applied to vertical farming, a novel sustainable indoor agricultural method [28][30].

The remaining sections of the chapter present the methodology used to develop and validate the proposed approach, then provide an overview of the interactive platform developed, and finally, some results that validate the approach as an improvement over the current more traditional paper-based method.

3.2. Methodology

The methodology followed to develop an ontology-based graphical user interface for the aquaponics 4.0 learning factory environment is shown in Figure 3-1.

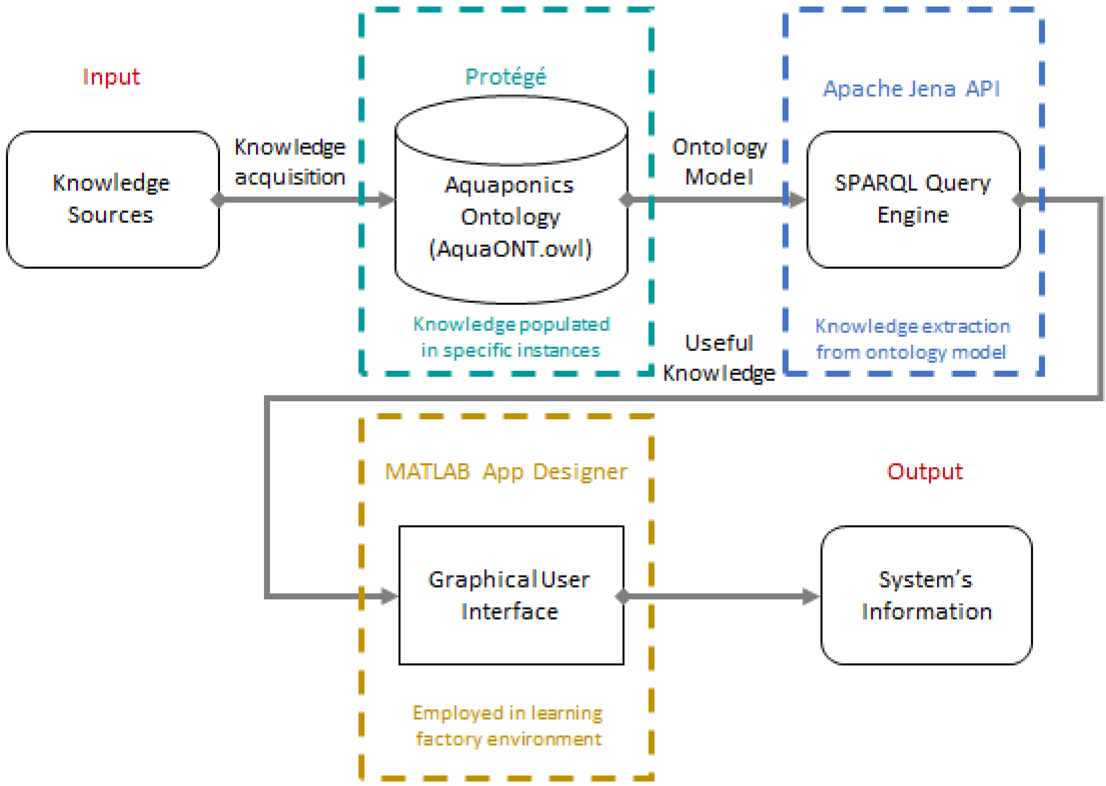

Figure 3-1. Methodology to develop ontology based graphical user interface for aquaponic 4.0 learning factory setup

First, a predefined aquaponics ontology model, *"AquaONT"* is updated and populated with relevant system knowledge associated with energy source and consumption, energy-efficiency, and demand [100]. The information stored is extracted from the system continuously, from sensors, for example, and from experts' knowledge. Then, the existing and inferred knowledge is extracted from the ontology model using SPARQL queries on Apache Jena API [101]. The results from SPARQL queries are saved in *.csv* format, making it convenient to access the ontology knowledge across various platforms. MATLAB app designer module is employed to develop a graphical user interface (GUI). Finally, the .csv file is imported into GUI, and a set of governing equations are developed to obtain useful information for the energy-efficient aquaponic 4.0 system's development [38].

To validate the proposed method, anonymous engineering students with no prior knowledge of the platform, with no knowledge of aquaponics or biological sciences, and with no connection to the learning factory volunteered to assess its viability. Also, a formative assessment is designed consisting of a performance rating scale [102] that enables users to provide feedback on the interactive methods tested [103].

3.3. Platform Development

The Aquaponics 4.0 graphical user interface platform provides a digital interactive learning approach to design energy-efficient hydroponic and aquaculture components to investigate Aquaponics 4.0 systems. Knowledge from the ontology model is retrieved using the SPARQL query engine and is represented using a graphical user interface (GUI). This GUI is designed using the MATLAB app designer tool and allows the user to make choices that eventually impact the model performance and energy-use efficiency. By enabling environment modification based on user behavior, a direct relationship between "decision" and "information feedback" is established, known as the "single-loop learning" process [104]. Such information empowers the learner's comprehension of the system, as his/her decisions can converge the physical world with the intended objective [105].

The GUI consists of six tabs, each capturing data from the ontology model and enhancing the user's experience. These tabs have been labeled as: 1) Aquaponics Overview, 2) Hydroponic Design, 3) Aquaculture Design, 4) AllFactory System, 5) Smart Sensors, and 6) Model Performance. A brief overview of each of these tabs is provided in Figure 3-2.

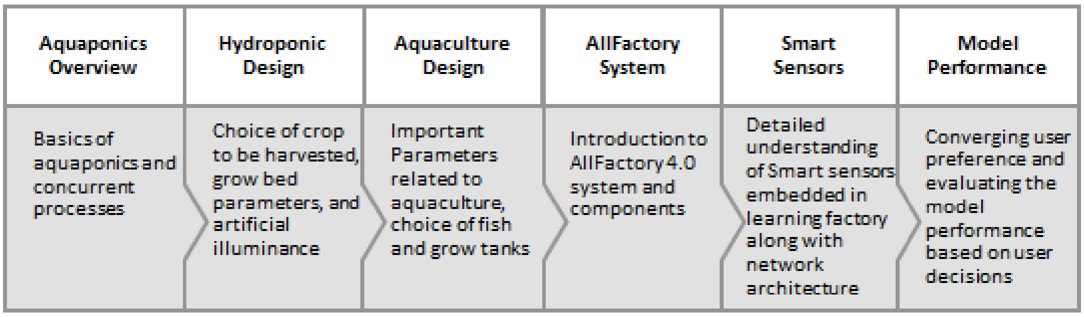

Figure 3-2. Aquaponics 4.0 interactive platform app overview

Offering high potential for display and innovation transfer, the proposed interactive graphical user interface guides the user through the basics of the knowledge being imparted [106] while allowing free exploration of all the accessible content. To achieve this objective, the GUI app starts with the aquaponics overview tab that expedites this process. Providing a holistic view of the aquaponics system, this tab introduces the user to major components and concurrent processes through a comprehensible illustration.

The hydroponic component acts as the nerve center and regulates the aquaponic system. The second tab (Figure 3-3) introduces the user to the hydroponic design, enabling them to choose all the elements that formulate the system: from the crop species, grow bed type, and number to the artificial illumination source that provides the photosynthetically active photons for crop growth. Furthermore, this tab also provides information on the energy-use efficiency of each lighting source to ensure optimal operation.

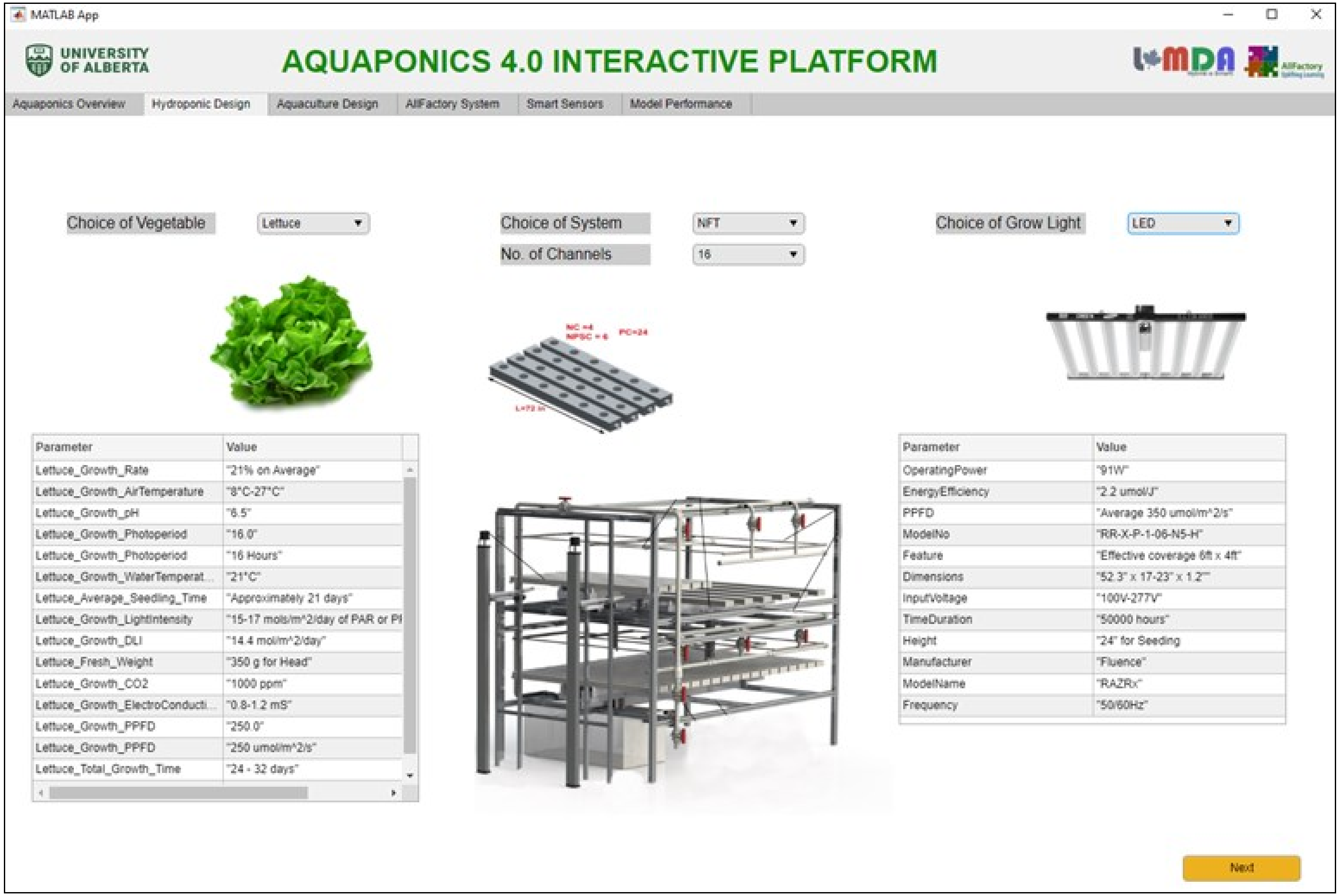

Figure 3-3. Illustration of Aquaponics 4.0 Interactive Platform Hydroponic Design tab

This is followed by the aquaculture design tab, whereby the user can select amongst the various species of fish as well as the fish grow tanks. Each choice made by the user populates data related to that particular entity from the ontology model, enhancing the user's comprehension of the system and providing brief information about the energy sources and sink and their impact on system performance.

The AllFactory and smart sensor tabs represent the physical system present in the learning factory. Encouraging the users to hover through the interactive illustrations, these tabs show detailed information about the various smart sensors embedded in the learning factory that gather real-time data to enable smart decision making and enhance energy-use efficiency. Furthermore, users are familiarized with the current system architecture used for data storage and retrieval. Finally, the model performance tab converges all user choices and displays the impact of those decisions on the energy-use efficiency, and the aquaponics system in general. Main parameters such as system performance, harvest intervals for crops and fish, or energy consumption are highlighted in this tab, allowing the users to understand the outcome of their decisions.

3.4. Results

Finally, the platform is to be validated using a formative assessment. This assessment is customized with core parameters to fit the user population specific to the learning factory use. These parameters have been listed in Table 3-1. Standard statements are generated for each of these parameters by using a narrative process, with scores ranging from 1 to 5 (1 being the lowest rating and 5 the highest). Users are then asked to rate each of the parameters based on their level of understanding and experience.

Table 3-1. Core parameters to evaluate Aquaponics 4.0 interactive platform

No	Parameter	1	2	3	4	5
1	Clarity	Complex	Fairly Complex	Average	Fairly Simple	Simple
2	Time Management	Onerous	Fairly Exhausting	Average	Fairly Swift	Swift
3	Practicality	Abstract	Fairly Abstract	Average	Fairly Practical	Practical
4	Effectiveness	Ineffective	Fairly Ineffective	Average	Fairly Effective	Effective
5	Relatable	Unrelated	Fairly Unrelated	Average	Fairly Related	Related
6	User Guided	Wandering	Fairly Wandering	Average	Fairly Guided	User Guided

The result of the formative assessment is plotted using a radar graph which provides a virtual representation of user experience [107]. This radar graph is broken into six core parameters as listed before. The results from both traditional as well as interactive approaches are overlaid on the same graph, enabling a head-on comparison.

For this study, an experiment is conducted involving 20 participants. Participants are asked to go through the AllFactory 4.0 user manual, currently in use for designing systems in the learning factory, followed by an initial assessment questionnaire. Then, the aquaponics 4.0 interactive platform is introduced, and participants are requested to fill out the assessment questionnaire once again. By comparing the users' assessment of both methods, insight into the impact of the change of platform is gained. The results from the two assessments are presented in Table 3-2, and plotted on the radar graph, illustrated in Figure 3-4.

Table 3-2. Results from case study highlighting mean, standard deviation, and variance of the recorded data

Parameter	Mean		Standard Deviation		Variance	
	Traditional	Interactive	Traditional	Interactive	Traditional	Interactive
Clarity	2.2	4.3	0.60	0.46	0.36	0.21
Time Management	2.1	4.1	0.54	0.30	0.29	0.09
Practicality	3.2	3.5	0.40	0.50	0.16	0.25
Effectiveness	2.9	4.6	0.70	0.66	0.49	0.44
Relatable	4.3	4.5	0.64	0.67	0.41	0.45
User Guided	2.8	4.1	0.75	0.54	0.56	0.29

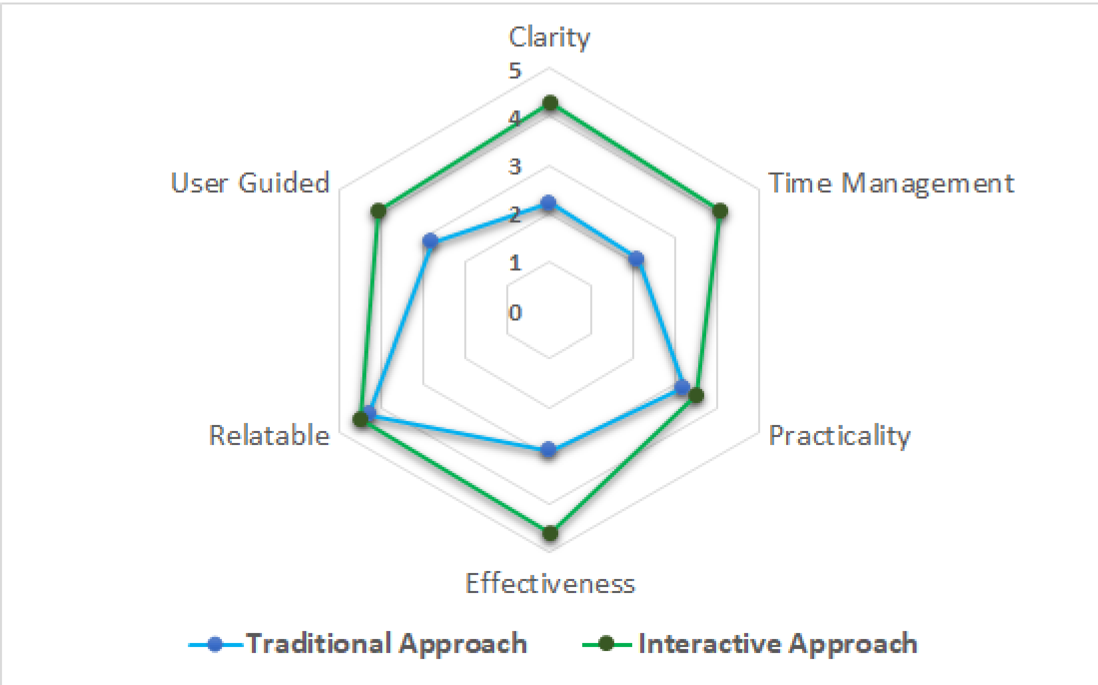

Figure 3-4. Radar graph comparing traditional vs interactive approach

Survey results provide an insight into the user experience of the two approaches, with the interactive approach securing higher ratings in almost all core parameters. Though "practicality" and "relatability" parameters are rated quite similar in both the approaches, interactive method excels in making the transdisciplinary energy-efficient concepts simple, swift, effective, and user friendly.

3.5. Future Work

An interactive graphical user interface allows for an expeditious transfer of transdisciplinary knowledge among users. The platform obtains relationships between different classes and the corresponding energy source/sink using a predefined ontology model, AquaONT. While this facilitates the understanding of energy-use efficiency within aquaponics, as well as interactive teaching in a learning factory environment, it does not dispense the real-time status of various components and subsystems within the learning factory. Involving concrete realization of physical entities in a virtual environment, digital twins modulate and optimize the learning factory using a digital copy of physical systems [25]. Future work includes integrating real-time energy monitoring and control with interactive platforms using intelligent sensors, digital twins, and the Internet of Things (IoT), enhancing the user experience and comprehension with regard to energy-efficient aquaponics operation.

3.6. Conclusion

This chapter provides a knowledge-based ontology model to understand and design energy-efficient hydroponic and aquaculture components for aquaponics 4.0 systems. This chapter proposes an interactive graphical user interface (GUI) designed using the MATLAB app designer tool. The GUI extracts knowledge from an ontology model, AquaONT, and enables environment modification based on client behavior. The model establishes a direct relationship between user decisions and energy demand, empowering users' comprehension of the system by providing valuable information feedback. Head-on comparison of the traditional versus interactive approach is performed in the case study, reveling the positive impact of interactive GUI on the transdisciplinary understanding and comprehension of energy-efficient aquaponics operation.

Chapter 4 Comparison of Energy-use Efficiency for Lettuce Plantation

Part A. Comparison of Energy-use Efficiency for Lettuce Plantation under Nutrient Film Technique and Deep-Water Culture Hydroponic Systems

Traditional soil-based agriculture practices are facing threats in the form of unpredictable weather patterns owing to rising temperatures, depleted soil productivity due to continuous cultivation, reduced per capita land availability on account of rising population, and, more importantly, poor water management leading to wastage of the most precious resource, water [108]. Modern techniques that rely on soil-less production, such as hydroponics and aquaponics, can complement conventional approaches to ensure a productive and ecologically sustainable food supply chain [109]. Such systems allow the increased quality of produce gained by avoiding soil-borne diseases, reducing exposure to fertilizers and pesticides, and enabling better control of environmental parameters, such as temperature, relative humidity, and light intensity, among several other variables [110]. At the same time, the energy demand of advanced agricultural systems that can be operated in harsh weather conditions and indoor facilities using artificial illuminance instead of the traditional solar radiation needs to be investigated to examine the applicability of these emerging technologies [49].

Energy conservation opportunities in closed plant production systems have been widely discussed; however, a comparison of energy-use efficiency (EUE) for different types of hydroponic systems is lacking. The first part of chapter four compares the EUE of two different hydroponic systems, namely nutrient film technique (NFT) and deep-water culture (DWC), within an aquaponics facility and further evaluates the growth dynamics and energy use of *Lactuca sativa L.* (Little gem) plantation.

4.1. Hydroponics – Soilless Alternative

Hydroponics is a class of horticulture that involves cultivating plants by exposing their roots to a liquid nutrient solution. Instead of the traditional approach of using soil, crop roots can be physically supported by inert media such as gravel, pearlite, rockwool, or other substrates. Distinguished as an engineered way of vegetation, hydroponics technique utilizes a soilless growing medium along with an enriched nutritive solution tailored to meet plant-specific needs and ensure growth and development [23]. Such systems minimize resource wastage as the nutrient-rich solution can be reused for maximum efficiency, achieving the highest yields by utilizing much less water per gram of produce [111]. Hydroponic systems have also been designed in coherence with aquaculture, labelled as aquaponics – a merger of hydroponics and aquaculture that work in a symbiotic environment promoting resource efficiency and sustainability [18], [28].

Removing the barrier between crop and its nutrients, hydroponics provides roots with direct access to water, oxygen, and other supplements to enhance growth and vegetation. This access can be achieved through different arrangements and is what differentiates the various types of hydroponic systems. Based on the mode of nutrient delivery and water distribution, hydroponic systems can be mainly classified as:

- Nutrient film technique (NFT)
- Deep water culture (DWC)
- Aeroponic system

4.1.1. Nutrient Film Technique (NFT)

A recirculating type of hydroponic system NFT comprises growing channels through which a layer of nutrient solution, typically 1-2 cm high, circulates with the help of mechanical pumps [38]. Such systems have great potential for automation and optimizing plant density; however, limited water availability and premature root system aging pose significant constraints in the production of crops with over 4 – 5 months of growth cycle [110]. One of the main advantages of the NFT system is how it handles the supplement solution. The recirculating nutrient-rich water can maintain healthy oxygen levels for plant growth and development and is one of the main reasons for its popularity amongst hydroponic enthusiasts. Furthermore, this setup requires minimal to no growing media and thus decreases the potential pH fluctuations that may occur otherwise.

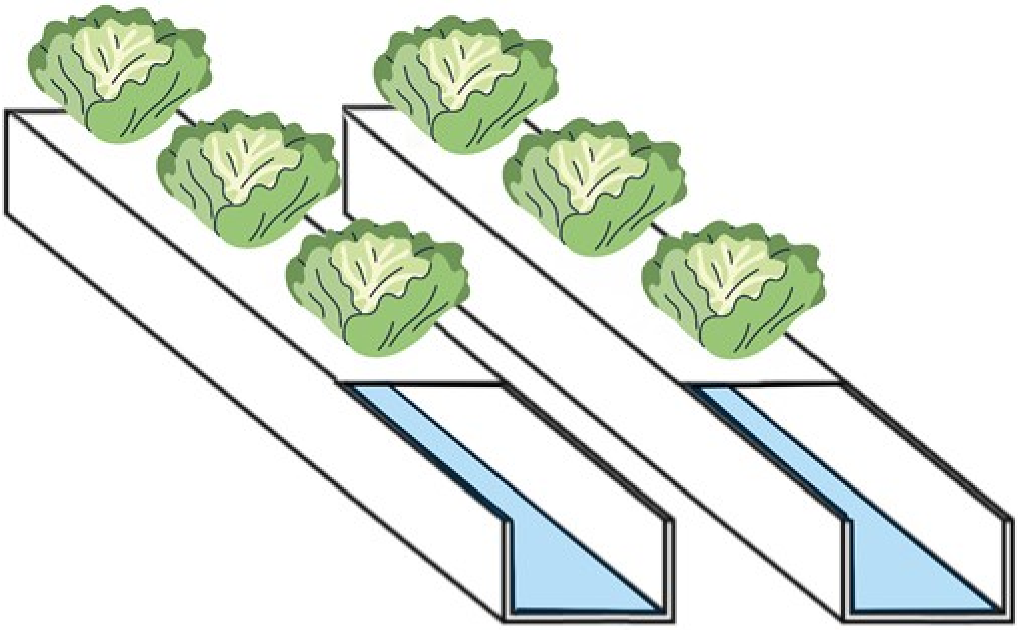

Figure 4-1. Schematic view of NFT hydroponic system

4.1.2. Deep Water Culture (DWC)

DWC hydroponic systems are of stationary type and comprise floating rafts that support plants placed over containers filled with nutrient-rich water. Such systems require minimum cost and supervision but possess limited scope for automation [112]. The inexpensive nature and relatively easier maintenance requirement of the DWC hydroponic system attract many growers. However, there are certain drawbacks to this type of setup. DWC systems are not recommended for larger plants or ones with longer growing periods. Furthermore, plant roots require oxygen for growth and development, without which they may drown. Thus, oxygen monitoring and control become vital for DWC hydroponic growers. The oxygen levels necessary for plant growth and development are maintained using air bubblers or venturi systems.

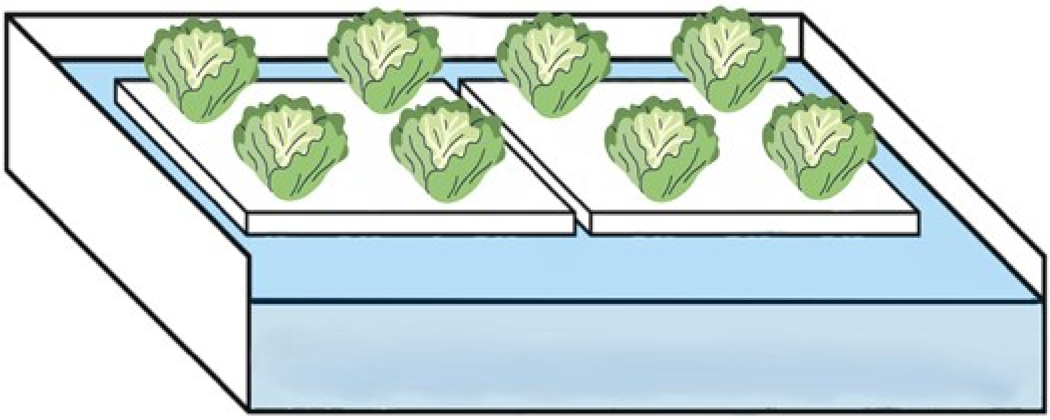

Figure 4-2. Schematic view of DWC hydroponic system

4.1.3. Aeroponic System

A less popular hydroponic system, aeroponics, works by exposing plant roots to a fine spray of nutrient-rich solution. Horizontal or vertical panels support plants, allowing the suspended roots to encounter the nutrient-rich solution sprayed directly on them using static sprinklers [21]. Aimed at smaller horticulture species, aeroponic systems require high investment and running costs leading to less popularity of such hydroponic systems. Furthermore, the nozzles run a risk of getting clogged which can have dire effects on the plants. On the bright side, this system allows the roots greater exposure to oxygen, thus resulting in enhanced growth and development.

Though much research has been published on enhancing the energy efficiency of modern agricultural technologies, there exists limited literature comparing the energy-use efficiency of NFT and DWC hydroponic systems in an aquaponic setup [9], [58], [66], [70]. As the two hydroponic systems tested are mechanically and conceptually distinct, they consume different amounts of energy and generate varying yields.

4.2. Material and Methods – NFT vs DWC

The experiment to compare lettuce energy-use efficiency under different hydroponic conditions is performed in Allfactory 4.0, an aquaponics facility situated at the University of Alberta, Canada, which focuses on advanced digital manufacturing processes applied to vertical farming and closed plant production systems [25], [28], [30], [93], [113].

4.2.1. Environmental Conditions

Little gem lettuce (*Lactuca sativa L.*) is chosen for this experiment, as it is ideal for small scale vertical farms due to its compact head size [114]. Having a germination rate of 93%, 50 seeds (Little Gem LT476, west coast seeds, British Columbia, Canada) are placed in growth chambers with ambient temperature of 18°C and 70% relative humidity. These seeds are irradiated with light-emitting diode (LED W-SF10, Wills, Texas, USA) for a 12-hour (12 hours light / 12 hours dark) photoperiod. Twenty-one days after sowing, 40 healthy lettuce seedlings are transplanted in rockwool cubes (Hydroponic mineral wool cubes, zxcv-de1-396, Holland Industry, Ontario, Canada).

Twenty of these rockwool cubes are placed in the NFT system (3 x 2.8 ft^2) attached to a sump filled with 20 gallons of water mixed with nutrient solution (Liquid plant food 4-3-6, 9401-0QZ, AeroGarden, Colorado, USA) containing 4.0% total nitrogen (N), 3.0% available phosphate (P2O5), 6% soluble potash (K20), 1% calcium (Ca) and 0.5% magnesium (Mg) per liter. This supplement rich water is siphoned into the system using a submersible pump (Pomp800, Hydrofarm, California USA). The remaining twenty rockwool cubes are accommodated in the DWC system (2 x 4 ft^2) loaded with 20 gallons of the same nutrient rich solution. Two air bubblers (Air stone ASD-040, Pawfly) connected to two identical air pumps (HG-811, Hygger) are used to disperse dissolved oxygen throughout the system. The two systems are illuminated using continuous irradiance light-emitting diodes (LED RAZRx RRR-X-P-1-06-N5-H, Fluence Bioengineering, Texas, USA) with maximum photosynthetic photon flux (PPF) of 200 $\mu mol \cdot s^{-1}$. Since the two systems differ in dimensions, the intensity of the light is optimized such that both the systems receive similar photosynthetic photon flux density (PPFD). Spectral scans are recorded at 25 cm from the lighting source at four corners and the center of each system using a spectroradiometer. PPFD for NFT system was found to be 258.33 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and that for DWC system was 269.10 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Light source spectrum has been illustrated in Figure 4-3.

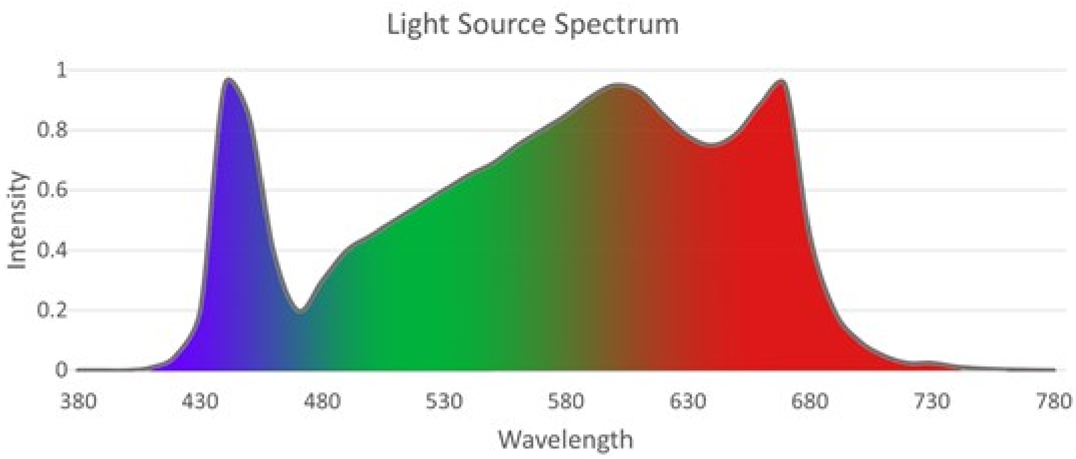

Figure 4-3. Artificial illuminance light source spectrum [adapted from [115]]

Both the systems are set up in an indoor aquaponics facility. The heating, cooling, and air conditioning is provided by building facility services and controlled using thermostat. The smart sensor (WS1 Pro, UbiBot, Texas, USA) is employed to monitor room temperature, relative humidity, and illumination at constant intervals. Furthermore, electroconductivity (Pencon Conductivity Pen, Bluelab, New Zealand) and pH (pH Pen, Bluelab, New Zealand) values are also recorded and balanced for both systems. The obtained data is logged for the entire period from seeding to harvesting to ensure the study is commensurable. The daily average value for those parameters for the entire duration of lettuce growth has been displayed in Table 4-1.

Table 4-1. Parameter values maintained for NFT and DWC hydroponic systems during growth cycle

Hydroponic System	Relative Humidity (%)	Ambient Temperature (°C)	PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	EC (dS/m)	pH
NFT System	70.2	18.8	258.33	1.26	5.9
DWC System	70.2	18.8	269.1	1.27	5.9

4.2.2. Growth Characteristics and Energy-use Efficiency

Lettuce seeds are placed in both hydroponic systems, NFT and DWC, for a period of 5 weeks. After plantation cycle, the lettuce is harvested and growth characteristics, such as plant fresh weight, shoot and root weight, leaf count, plant height, plant width, and root length are measured. An electronic scale (Digital scale EK9000, Etekcity, China) is used to determine the fresh biomass of lettuce.

Throughout the duration of plantation, the energy consumption of the LED lights and water and air pumps is measured using smart energy meters (Smart plug B08CVSSVWP, Emporia energy, Colorado, USA) and the data is transmitted to a cloud platform. Energy-use efficiency (EUE) is calculated by dividing the plant fresh weight to the total kilowatt hour energy consumption (g. kWh-1) after 5 weeks of treatment. This is represented by equation (1) [70].

$$EUE = \sum Plant\ Fresh\ Weight \div \sum Energy\ Consumption \qquad (1)$$

4.2.3. Statistical Analysis

Prior to transplantation, lettuce seedlings are randomized going into the two hydroponic systems. Data related to lettuce growth characteristics is captured after harvesting the produce, and statistical analysis of this recorded data is performed using an unpaired t-test. This test compares the growth characteristics of both NFT and DWC grown hydroponic lettuce, which are two independent and unrelated groups. It then determines if there exists any significant difference between the lettuce growth characteristics. These statistics along with the energy consumption results, are eventually utilized to compute the energy-use efficiency (EUE) of lettuce plantations under nutrient film technique and deep-water culture hydroponic systems.

4.3. Results and Discussion – NFT vs DWC

4.3.1. Energy Consumption – NFT vs DWC system

Energy demand for a typical indoor plantation facility is mainly in the form of environmental conditioning (heating, ventilation, and air conditioning), artificial illuminance, and mechanical systems [35]. As both the systems are placed in the same facility, adjacent to each other, heating, ventilation, and air-conditioning (HVAC) load remain constant for both systems and is therefore not considered during this analysis. Energy consumption for the artificial illuminance and the water and air pumps for both hydroponic systems has been shown in Figure 4-4.

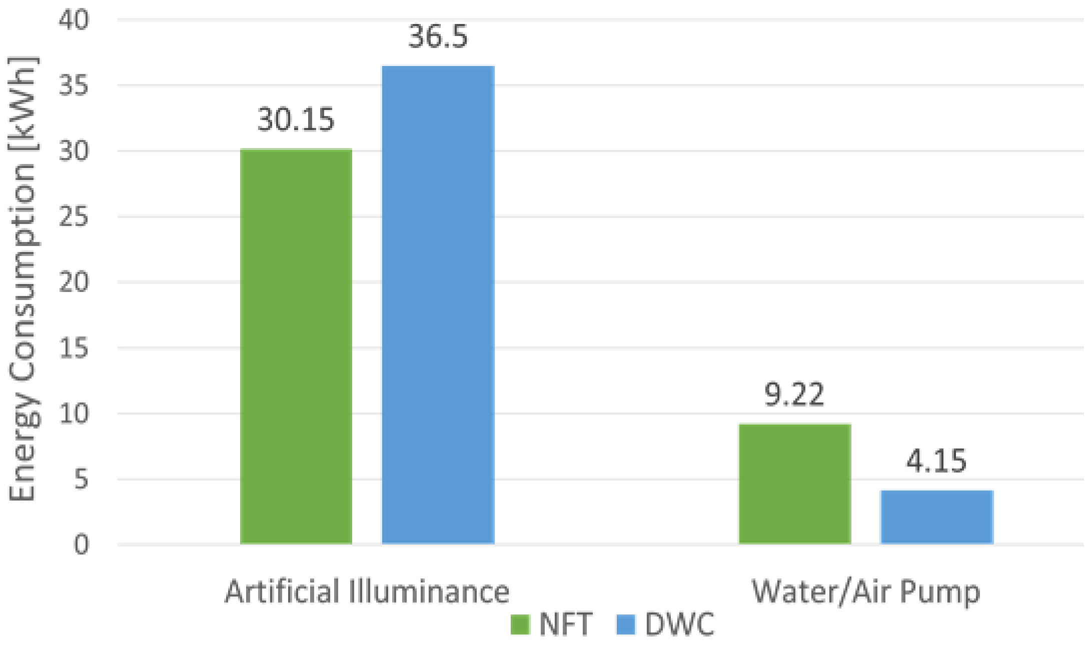

Figure 4-4. Energy consumption for NFT and DWC hydroponic system

The higher energy consumed by the DWC system for artificial illuminance can be attributed to the higher light intensity employed by the system to ensure that similar photosynthetic photon flux density (PPFD) is received by crops in both DWC and NFT systems and that the environmental conditions are identical. However, the NFT system requires more energy for water circulation and exceeds the mechanical energy demand of the DWC hydroponic system, employs a relatively small air pump to maintain water oxygen levels. In total, for this experiment, the DWC system consumes 3.25% more energy than the NFT system with the same number of lettuce crops.

4.3.2. Growth Characteristics – NFT vs DWC system

The growth of lettuce cultivated under LED artificial illuminance for a period of 5 weeks is influenced by the type of hydroponic system as depicted in Table 4-2. A sample size of 20 lettuces is used for this statistical comparison, and an unpaired t-test is performed to validate the results. Important growth characteristics, such as fresh plant weight, shoot, and root weight, are significantly higher in the NFT hydroponic system. Other parameters such as plant height, plant width, and leaf count are found unaffected by the type of hydroponic system employed.

This conclusion is drawn after obtaining the P-value of the two-tailed t-test for the recorded data. This statistical method is user to determine if the data at hand is sufficient to support a particular hypothesis, in this case, whether both NFT and DWC hydroponic lettuce growth characteristics have similar means. The null hypothesis indicates that both NFT and DWC hydroponic lettuce growth characteristics have similar means. The P-values obtained by the test, highlighted in Table 4-2, denote the probability of null hypothesis being correct.

Table 4-2. Lettuce growth characteristics under NFT and DWC hydroponic systems based on a sample size of 20 lettuce plants

	Plant Fresh Weight (g)		Shoot Weight (g)		Root Weight (g)		Plant Height (cm)		Plant Width (cm)		Root Length (cm)		Leaf Count	
	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC
Total	1234.2	977.4	905.9	829.4	323.4	145.8	-	-	-	-	-	-	309	297
Max	90.7	87.8	72.4	73.6	24.0	15.6	14.0	12.0	23.0	21.3	44.0	54.1	25	20
Min	40.2	32.7	24.2	25.9	6.7	3.8	7.5	8	8.0	11.3	23.0	27.7	9	12
Mean	61.7	49.9	45.3	41.3	16.2	7.3	10.4	10.3	15.6	14.3	33.3	37.5	15.5	14.9
Median	58.0	47.2	43.5	38.5	17.6	6.4	11.0	10.6	14.0	14.4	32.0	37.6	14.0	15.0
Standard Deviation	13.9	14.2	13.3	11.8	4.6	3.0	2.0	1.0	4.0	2.5	6.6	6.9	3.8	2.0
P-value for two tailed test	0.0115		0.2289		0.0001		0.4333		0.709		0.0132		0.6118	

The mean plant fresh weight for NFT-grown lettuce is found to be 61.7 grams, 23.6% higher than DWC-grown lettuce. Similar patterns are observed for NFT-grown lettuce shoot and root weight, with mean values of 4.0 grams and 8.9 grams greater than the DWC system, respectively. Though the NFT system witnesses higher lettuce root weight, the average root length for DWC grown lettuce is found to be 12.6% greater. Both the systems result in a similar leaf count of about 15 leaves per lettuce crop. Based on these results, the NFT system performs better as compared to the DWC system in producing hydroponic lettuce with higher biomass. A pictorial depiction of hydroponic lettuce grown in NFT and DWC is shown in Figure 4-5.

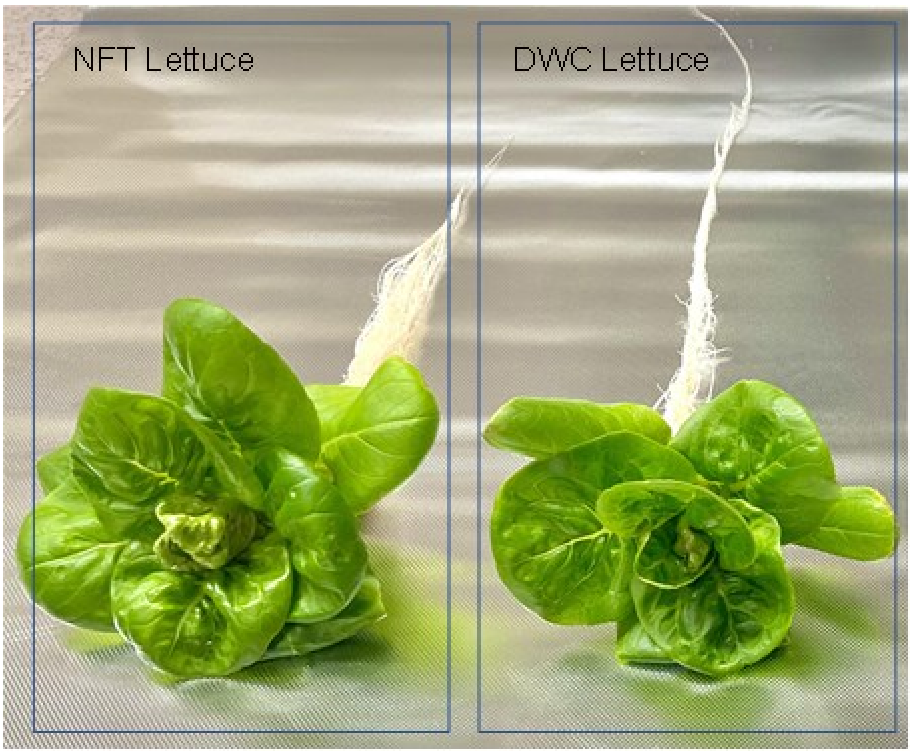

Figure 4-5. Pictorial representation of NFT and DWC grown hydroponic lettuce

4.3.3. Energy-use Efficiency – NFT vs DWC system

To evaluate energy consumption levels of hydroponic lettuce plantation more intuitively and provide qualitative results for commercial hydroponic lettuce production, data gathered from the growth characteristics and the energy consumption is utilized to come up with the energy-use efficiency for the two hydroponic systems. An EUE of 31.34 g. kWh^{-1} is recorded for the NFT grown hydroponic lettuce, outperforming the DWC system with a EUE of 24.53 g. kWh^{-1}. These results have been plotted in Figure 4-6.

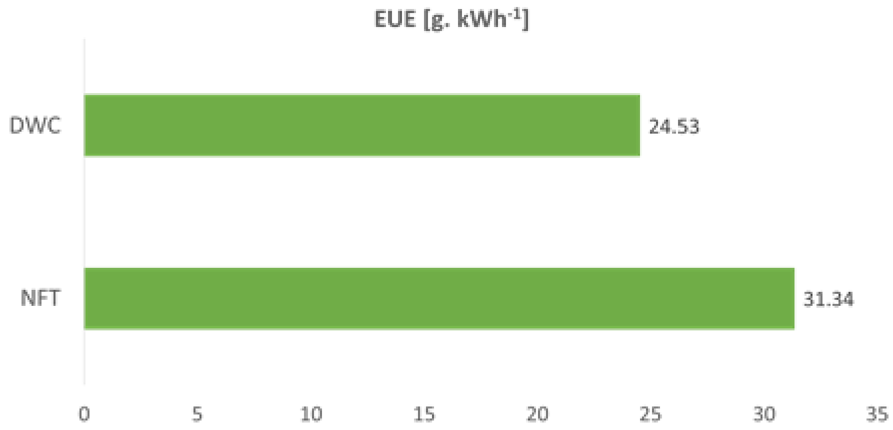

Figure 4-6. EUE comparison of NFT and DWC grown hydroponic lettuce

The industrialization of modern agricultural plant factories and aquaponics is hindered by excessive energy consumption and thus calls for improving produce yield per unit of energy consumed [68]. In this experiment, the 27.7% higher EUE associated with NFT-based hydroponic system can be attributed to two factors. The first being the enhanced growth of lettuce plants due to better nutrient flow and optimal plant density during crop cycles, and the second being a reduced energy consumption associated with the NFT hydroponic system in general [23]. As such, this study proposes the use of NFT hydroponic systems for lettuce plantations in indoor plant factories and aquaponics facilities.

Part B. Comparison of Energy-use Efficiency for Lettuce Plantation under Pulsed and Continuous LED Irradiance using NFT Hydroponic System

Urban agriculture relies on new plant production systems that offer minimal environmental impact or high resource use efficiency. Broadly categorized into greenhouses or closed plant production systems (CPPS), the benefit of each type differs significantly. Perhaps the most futuristic concept of CPPS is aquaponics, defined as a merger between hydroponics and aquaculture, which imitates the natural systems and offers to be an ecologically green and sustainable form of urban agriculture. A schematic representation of NFT hydroponic-based aquaponics system present in AllFactory 4.0 is shown in Figure 4-7 [116].

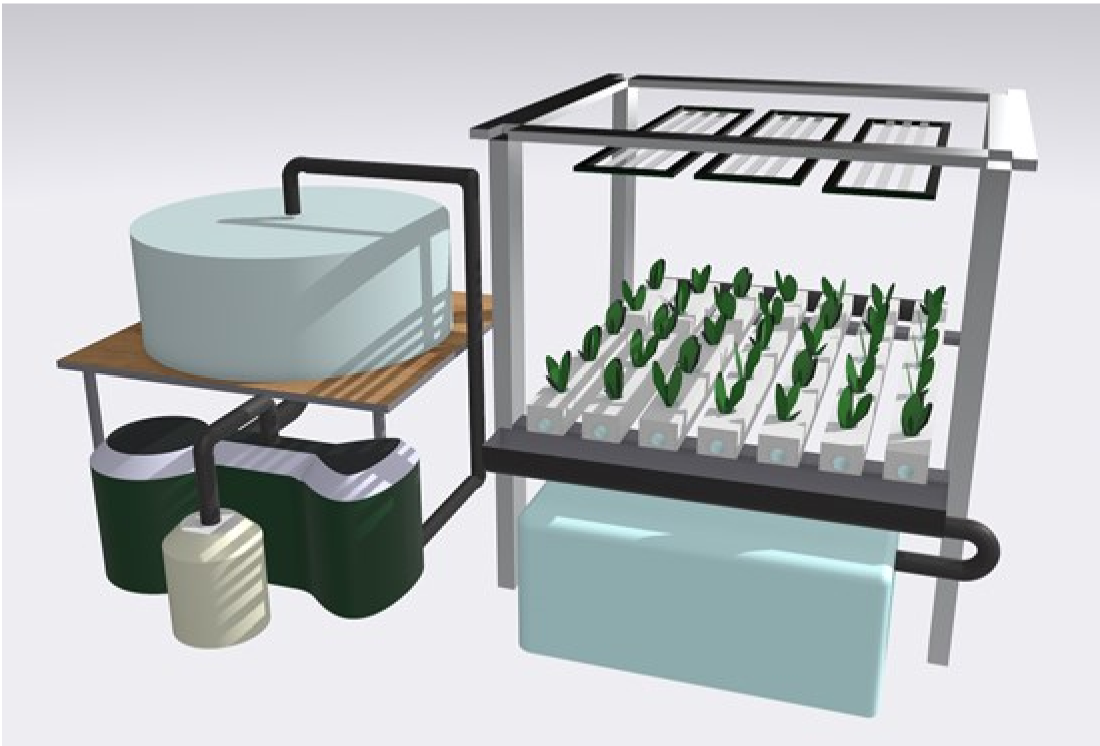

Figure 4-7. NFT based indoor decoupled aquaponics system

The highly controlled environment leading to increased yields, high water efficiency, and close proximity to the customer market are some of the major advantages posed by such CPPS. Another advantage of indoor hydroponics is its tolerance against seasonal changes and harsh weather conditions, leading to higher annual productivity as compared to traditional agricultural practices [117]. However, indoor hydroponics require artificial illuminance and heating, cooling, and ventilation apart from the water/air circulation leading to increased energy consumption when compared to greenhouse facilities but offering the advantage of year-round production [20]. The environmental footprint of such systems depends mostly on the energy-use efficiency for lighting and supplemental conditioned airflow and is usually assessed on a per-project basis [20].

Energy consumption is considered as one of the main challenges for indoor hydroponic and aquaponic facilities in terms of sustainability and environmental footprint [35], [118], [119]. Implementation of energy-efficient solutions such as light-emitting diodes (LEDs) for artificial illuminance and the use of renewable energy sources for heating, ventilation, and air conditioning has significantly reduced the ecological consequences of modern agriculture [68], [120]. The energy demand of a typical hydroponic facility is illustrated in Figure 4-8.

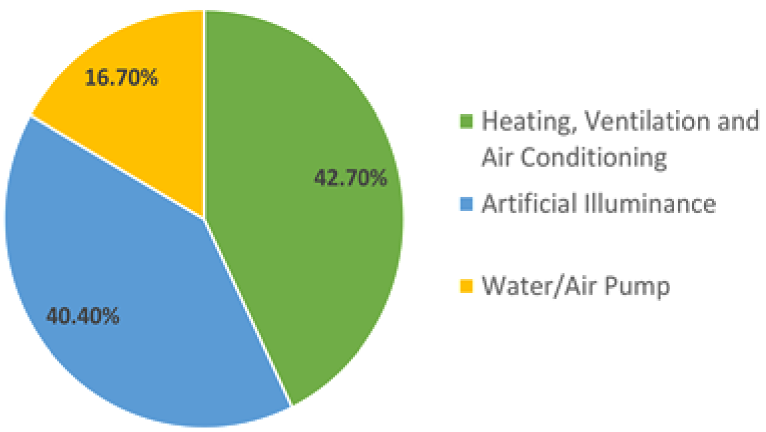

Figure 4-8. Energy demand of a typical hydroponic facility [adapted from [35]]

4.4. Artificial Illuminance

Artificial illuminance is an essential component of indoor hydroponics that provides the indispensable energy to plants for carrying out photosynthesis. The incoming radiation is absorbed by plant photoreceptors, converting atmospheric carbon dioxide to carbohydrates, and is critical for plant growth and morphological development. The type of artificial lighting deployed plays a crucial role in determining the energy-use efficiency and hydroponic yield. Various studies in the past have tried to establish an energy-efficient lighting source for indoor hydroponics and aquaponics. Oliver et al. reported a higher average growth rate for plants illuminated with light-emitting diode (LED) irradiance when compared to fluorescent (FLO), induction (IND), and high-intensity discharge (HID) lamps [24]. Similar results were noted by Singh et al., claiming 75% energy savings associated with LEDs when compared HID irradiance [54]. In a separate study, Custódio et al. reported 17% better energy efficiency for LED systems when compared to traditional fluorescent lighting [62]. Furthermore, longer lifecycle and lower energy consumption associated with LED irradiance are attributed to lower life-cycle greenhouse gas emissions [49]. Due to lower energy consumption per unit yield, reduced surface temperature, compact design, and scope for tailoring light recipes, LEDs are recognised by researchers and plant growers as the principal source of artifical illuminance in plant factories [53], [121], [122]. Figure 4-9 shows the average growth rate measured in $g.m^{-2}.kWh^{-1}$ for swiss chard and beta vulgaris grown under four artificial lighting sources, light-emitting diode (LED), fluorescent (FLO), induction (IND), and high-intensity discharge (HID) lamps [24].

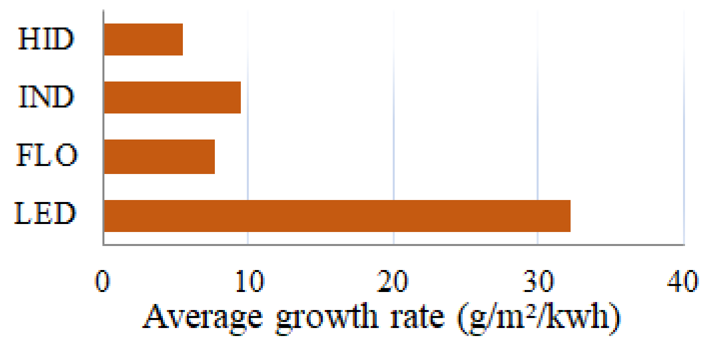

Figure 4-9. Average growth rate comparison using four artificial illuminance [24]

4.4.1. Light-Emitting Diode Photosynthetic Photon Flux Density

Optimizing artificial illuminance can ensure reduced energy consumption while maximizing plant growth and morphological development [123]. Various studies in the past have tried to understand the impact of photosynthetic photon flux density on the yield and quality of hydroponic produce [68], [77], [124]. Photosynthetic photon flux density (PPFD) can be defined as the amount of photosynthetically active radiation (PAR) received by plants each second per unit area [63]. Measured in $\mu mol.m^{-2}.s^{-1}$, optimal PPFD can result in higher biomass and increased energy-use efficiency [57]. Figure 4-10 highlight the LED PPFD range recommended for plant factories based on the literature analyzed in chapter 2.

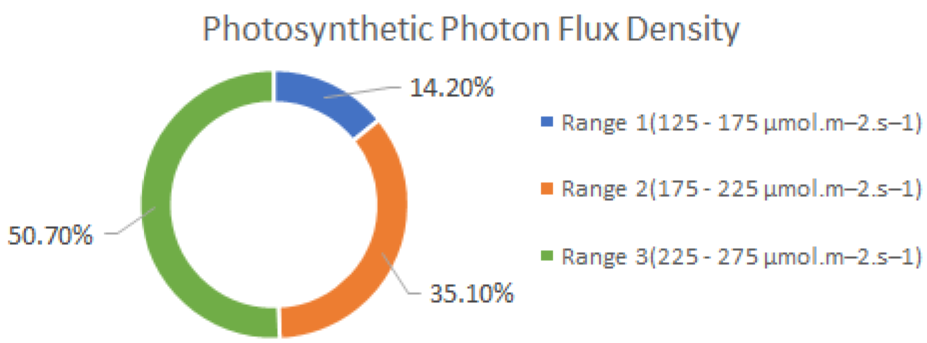

Figure 4-10. PPFD range recommended for LED artificial illuminance for indoor farming

4.4.2. Light-Emitting Diode Pulsed Irradiance

Pulsed irradiance refers to the rate at which electric current is passed through a light source. As such, a plausible strategy to reduce energy consumption in plant factories and hydroponic systems is to opt for a higher switching frequency, or pulsed irradiance [83]. Offering significant energy savings, the light spectrum of LEDs can be tailored in either a continuous or a pulsed fashion, referred to as the light recipe. The prime objective of using pulsed irradiance is to reduce power consumption without inhibiting plant growth and development [120]. Both continuous and pulsed light treatments can offer similar daily light integral, defined as the amount of photosynthetically active radiation (PAR) received by plants each day [58]. Son et al. investigated the impact of pulsed radiation on the growth of lettuce and observed significant energy savings using a duty cycle of 75% [120]. Lettuce net chlorophyll content and quantum yield were unaltered. Another study performed by Song et al. concluded that approximately 30%-50% of energy could be saved by opting for pulsed irradiation [80]. Similar results were observed by other authors, validating the positive impact of pulsed LED treatment on the energy-use efficiency of indoor hydroponics and aquaponics [82], [124]–[127]. Furthermore, plant fresh weight and photosynthetic activity of lettuce is found to be enhanced by employing pulsed LEDs, as suggested by earlier studies [128].

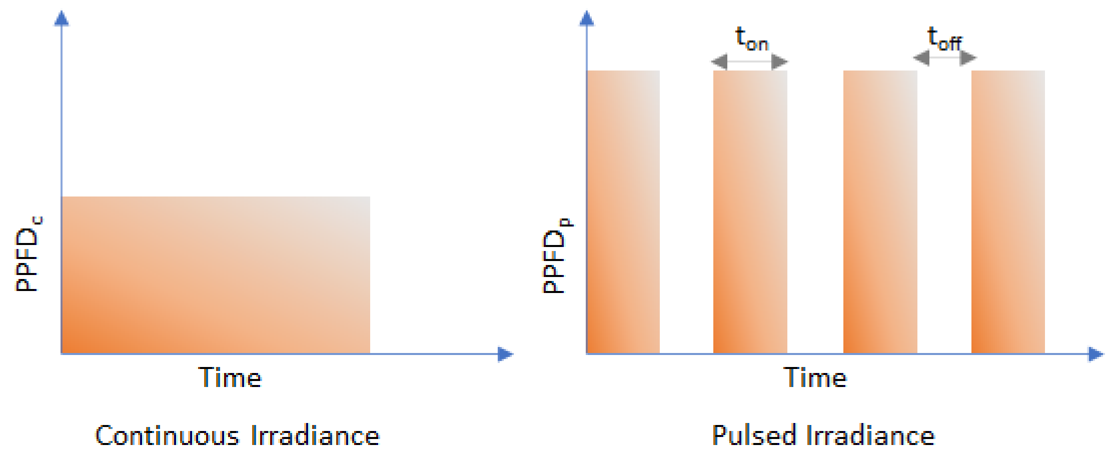

Figure 4-11. Continuous vs pulsed irradiation graphical representation (adapted from [124])

The results from the first part of this chapter indicated a better energy-use efficiency associated with a nutrient film technique-based hydroponic system. The remaining portion of this chapter tries to evaluate the impact of pulsed versus continuous LED irradiance on the energy-use efficiency of *Lactuca sativa L*. (Little gem) plantation in an NFT-based hydroponic system within an aquaponic facility.

4.5. Material and Methods – Pulsed vs Continuous Irradiance

This experiment to compare lettuce energy-use efficiency under pulsed and continuous irradiance for NFT based hydroponic system is performed in Allfactory 4.0, an aquaponics facility situated at the University of Alberta, Canada, which focuses on advanced digital manufacturing processes applied to vertical farming and closed plant production systems [25], [28], [30], [93], [113].

4.5.1. Environmental Conditions

The environmental conditions for this experiment are similar to the previous experiment comparing the energy-use efficiency of NFT and DWC hydroponic systems. Same seeds belonging to Little Gem lettuce (*Lactuca sativa L.*) are chosen for this experiment

(Little Gem LT476, west coast seeds, British Columbia, Canada). The seeds are placed in growth chambers with an ambient temperature of 18°C, relative humidity of 70%, and irradiated with a light-emitting diode (LED W-SF10, Wills, Texas, USA) for a 12-hour (12 hours light / 12 hours dark) photoperiod. Twenty-one days after sowing, 60 healthy lettuce seedlings are transplanted in Rockwool cubes (Hydroponic mineral wool cubes, zxcv-de1-396, Holland Industry, Ontario, Canada) and placed in the NFT based hydroponic system attached to a sump filled with 80 gallons of water mixed with nutrient solution (Liquid Plant Food 4-3-6, 9401-0QZ, AeroGarden, Colorado, USA) containing 4.0% total nitrogen (N), 3.0% available phosphate (P2O5), 6% soluble potash (K20), 1% calcium (Ca) and 0.5% magnesium (Mg) per liter. This supplement rich water is siphoned into the system using a submersible pump (Pomp800, Hydrofarm, California USA).

The system is divided into three phases, each containing 4 channels holding 20 lettuce seedlings. These phases are illuminated using light-emitting diodes (LED RAZRx RRR-X-P-1-06-N5-H, Fluence Bioengineering, Texas, USA), however, the mode of irradiance is different. Pulsed LED irradiance with frequency of 0.5 and 1 kHz is applied using a pulse width modulation device (PWM XY-LPWM, Yoochin, China) for phase 1 and 2 respectively, while phase 3 employs continuous irradiation. Based on the literature analyzed, a duty cycle of 75% is adopted for the pulsed illuminance, representing the relationship between time on (t_{on}) and time off (t_{off}), while the photoperiod is kept at 16 hours. Photosynthetic photon flux density for continuous mode ($PPFD_C$) is fixed at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. For pulsed irradiance, the photosynthetic photon flux density is denoted by $PPFD_P$ and can be obtained by equation (2) [124].

$$PPFD_P = \frac{PPFD_C \times 100}{Duty\ Cycle} \tag{2}$$

The daily light integral for pulsed illumination (DLI_P) defined as the amount of light supplied to the plants per day can be obtained by equation (3) [124].

$$DLI_P = N_P \frac{1}{1000000} \int_0^{t_{on}} (PPFD_P \times dx) \tag{3}$$

Where N_p represents the number of pulses and is calculated by multiplying the frequency in hertz (Fc) to the photoperiod. 1000000 represents the conversion factor between µmol and mol. Table 4-3 highlights the key parameters for all three phases.

Table 4-3. Parameter values maintained for NFT phases

NFT Phase	Irradiation Mode	Frequency (kHz)	Duty Cycle	PPFD (µmol·m^{-2}·s^{-1})
Phase 1	Pulsed	0.5	75%	266.6
Phase 2	Pulsed	1	75%	266.6
Phase 3	Continuous	-	-	200

The heating, cooling, and air conditioning is provided by building facility services and controlled using thermostat. The smart sensor (WS1 Pro, UbiBot, Texas, USA) is employed to monitor room temperature, relative humidity, and illumination at constant intervals. Furthermore, electroconductivity (Pencon Conductivity Pen, Bluelab, New Zealand) and pH (pH Pen, Bluelab, New Zealand) values are also recorded and balanced for all three phases. The obtained data is logged for the entire period from seeding to harvesting to ensure the study is commensurable.

4.5.2. Growth Characteristics and Energy-use Efficiency

Lettuce seeds are placed in NFT-based hydroponic systems for a period of 5 weeks. After the plantation cycle, lettuce is harvested, and growth characteristics, such as plant fresh weight, shoot and root weight, leaf count, plant height, plant width, and root length are measured. An electronic scale (Digital scale EK9000, Etekcity, China) is used to determine the fresh biomass of lettuce.

Throughout the duration of plantation, the energy consumption of the LED lights and water and air pumps is measured using smart energy meters (Smart plug B08CVSSVWP, Emporia Energy, Colorado, USA), and the data is transmitted to a cloud platform. Energy-use efficiency (EUE) is calculated using equation (1).

4.5.3. Statistical Analysis

Lettuce seedings are randomly selected prior to placing them in the three NFT-based hydroponic systems. Data related to lettuce growth characteristics is captured after harvesting the produce, and statistical analysis on this recorded data is performed using a one-way analysis of variance. This test compares the growth characteristics of NFT-based hydroponic lettuce grown in the three independent and unrelated phases. It then determines if at least one phase mean/median is different from the other. These statistics along with the energy consumption results, are eventually utilized to compute the energy-use efficiency (EUE) of lettuce plantation for pulsed vs continuous irradiation.

4.6. Results and Discussion – Pulsed vs Continuous Irradiance

4.6.1. Energy Consumption – Pulsed vs Continuous Irradiance

As stated in the earlier part of this chapter, energy demand for a typical indoor plantation facility is mainly in the form of environmental conditioning (heating, ventilation, and air conditioning), artificial illuminance, and mechanical systems [35]. For this experiment, all three NFT phases are placed adjacent to each other, and the heating, ventilation, and air-conditioning (HVAC) load remains constant. Furthermore, nutrient-rich water is siphoned from the sump using a single pump. As such, the three phases differ in the amount of energy consumed by artificial illuminance alone. This can be observed through Figure 4-12.

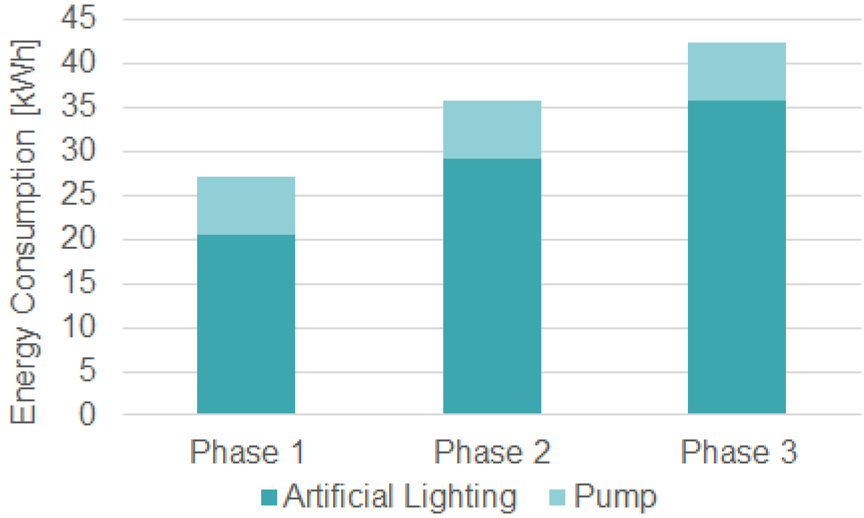

Figure 4-12. Energy consumption for different phases

The higher energy consumed by phase 3 can be attributed to continuous irradiance instead of the pulsed lighting employed by phases 1 and 2. In total, for this experiment with the same number of lettuce crops, phase 3 consumed 56.79% and 18.47% more energy than phase 1 and phase 2, respectively.

4.6.2. Growth Characteristics – Pulsed vs Continuous Irradiance

The growth of lettuce cultivated under LED artificial illuminance for a period of 5 weeks is influenced by the type of irradiation, i.e., pulsed vs continuous, as depicted in Figure 4–13. A sample size of 20 lettuces is used for this statistical comparison, and one-way analysis of variance is performed to validate the results. Important growth characteristics, such as plant fresh weight, shoot and root weight, and the number of leaves, are significantly higher for continuous LED irradiance (phase 3) as opposed to pulsed LED illumination (phase 1 and phase 2). However, within the pulsed irradiance, a frequency of 1000 Hz (phase 2) results in enhanced growth as opposed to a frequency of 500 Hz (phase 1). The number of leaves is comparable in phase 2 and phase 3 but is significantly less in phase 1. Other parameters such as plant height, root length, and plant width are found unaffected by the type of artificial illuminance employed. This conclusion is drawn after obtaining P-value for one-way ANOVA at alpha value of 0.05 for the recorded data, which tests the null hypothesis that hydroponic lettuce growth characteristics for all three phases with varying light recipes have similar means. The values greater than the significance level (0.05) denote the probability that the null hypothesis is correct. These results have been listed in Table 4-4.

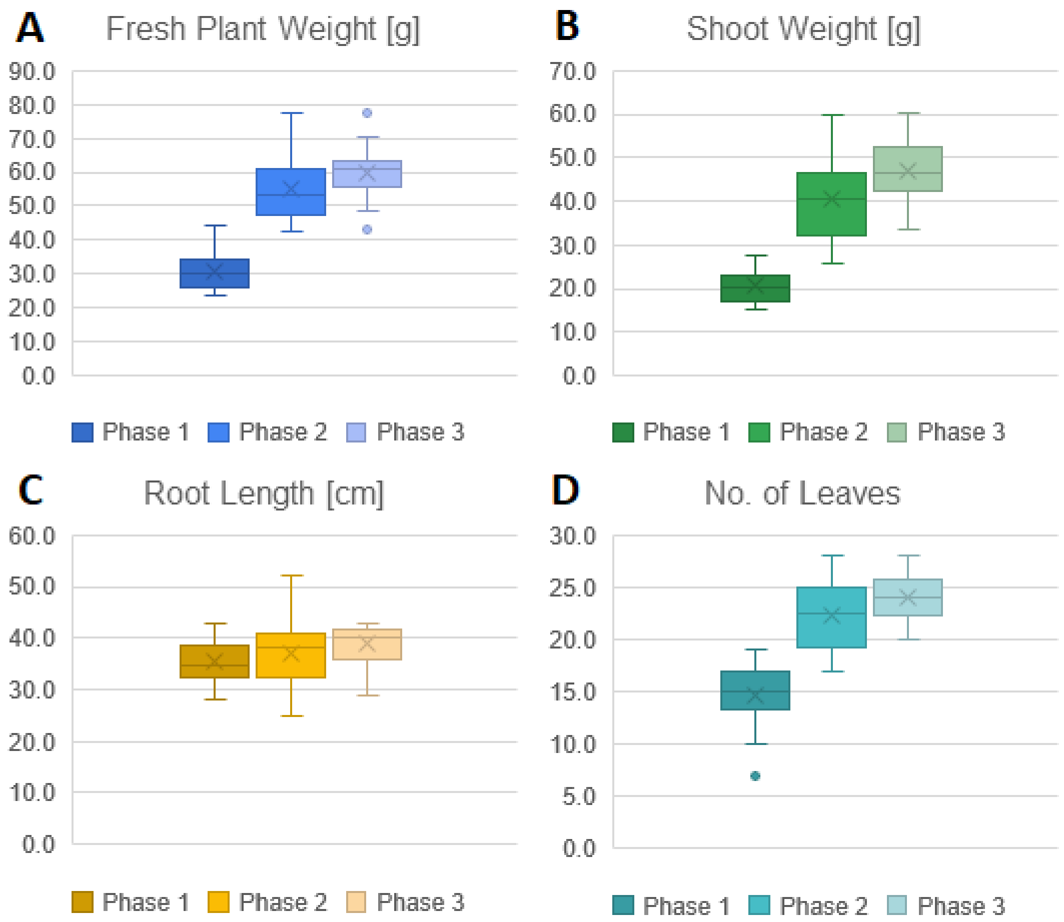

Figure 4-13. Growth characteristics for (A) Fresh plant weight in grams; (B) Shoot weight in grams; (C) Root length in cm; and (D) Number of leaves for different light treatments.

Table 4-4. Lettuce growth characteristics under three different light treatments based on a sample size of 20 lettuce plants. P1 – Pulsed LED irradiance with 500 Hz (Phase 1); P2 – Pulsed LED irradiance with 1000 Hz (Phase 2); P3 – Continuous LED irradiance

	Plant Fresh Weight (g)			Shoot Weight (g)			Root Weight (g)			Plant Height (cm)			Plant Width (cm)			Root Length (cm)			Leaf Count		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
Total	620.7	1100.6	1197.4	412	806.6	936.3	208.7	294	261.1	-	-	-	-	-	-	-	-	-	294	444	481
Max	44.3	77.6	77.3	27.5	59.6	60.2	16.8	19.6	17.1	13	12	12	17	17	15	52	52	43	19	28	28
Min	23.5	42.6	43.1	15.2	25.8	33.8	7.1	11.3	9.3	9	10	10	10	11	12	34	25	29	7	17	20
Mean	31	55	59.9	20.6	40.3	46.8	10.4	14.7	13.1	11.1	10.8	11.5	12.9	13	13.1	43.9	37.1	38.9	14.7	22.2	24.1
Median	30.4	53.2	61.2	20.4	40.6	46.5	9.6	14	12.6	11	11	11.5	12.5	12.5	13	44.5	38	40	15	22.5	24
Standard Deviation	5.3	10.1	7.3	3.6	9.9	6.7	2.7	2.2	2.2	1.1	0.7	0.6	1.8	1.8	1	4.5	6	4	2.7	3	2.1
P-value for one-way ANOVA	1.28E-16			7.15E-16			3.33E-06			0.06			0.89			0.08			8.56E-16		

The mean plant fresh weight for phase 3 grown lettuce is found to be 59.9 grams, 93.22%, and 8.90% higher than phase 1 and phase 2 grown lettuce, respectively. Similar patterns are observed for lettuce shoot weight. However, phase 2 witnesses a slightly higher lettuce root weight, the average root length for all three phases is comparable with a P-value of 0.08. All the three phases show similar lettuce height and width, with P-values of 0.06 and 0.89, respectively. Lettuce leaf count is significantly less, averaging at 15 leaves per lettuce plant for phase 1 with pulsed LED irradiance of 500 Hz, but the other two phases show comparable results with a 6.6% mean difference in the number of leaves. A pictorial depiction of hydroponic lettuce grown under the three phases with a different light recipe is shown in Figure 4-14.

Figure 4-14. Pictorial representation of hydroponic lettuce grown under different light treatments

4.6.3. Energy-use Efficiency – Pulsed vs Continuous Irradiance

Artificial lighting plays a key role in indoor hydroponics and aquaponics applications. To aid indoor commercial hydroponic lettuce production, energy-use efficiency for different lighting conditions, i.e., pulsed vs. continuous at different frequencies, is computed using the data gathered from lettuce growth characteristics and LED energy consumption. An EUE of 30.77 g. kWh^{-1} is recorded for phase 2 with 1000 Hz pulsed LED treatment, outperforming the EUE of 22.96 g. kWh^{-1} and 28.25 g. kWh^{-1} for phase 1 and phase 3, respectively. These results have been plotted in Figure 4-15.

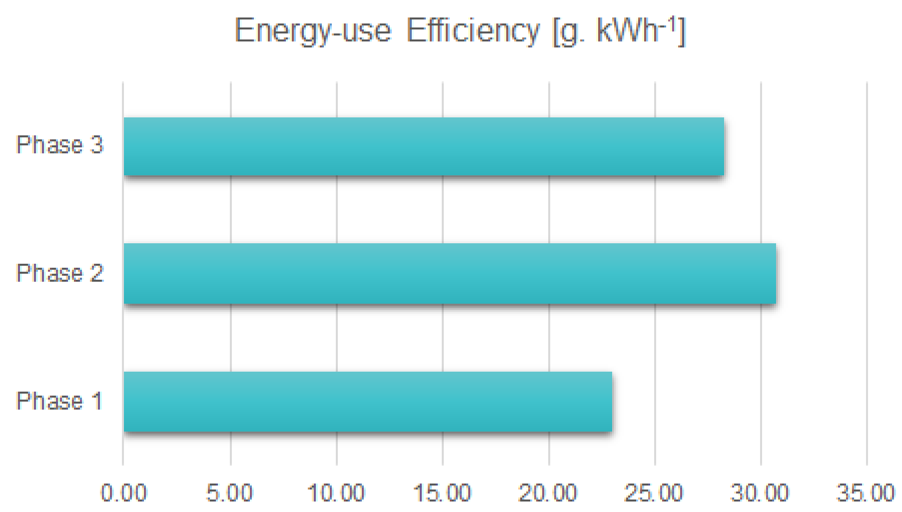

Figure 4-15. EUE comparison of hydroponic lettuce grown under different light treatments

Phase 1 with pulsed LED irradiance of 500 Hz recorded a 93% reduction in fresh plant weight and 23% lesser EUE values when compared to control (phase 3). Simultaneously, the fresh plant weight in phase 2 with pulsed LED treatment having a frequency of 1000 Hz was reduced by up to 8% when compared to the control. However, the EUE increased by 8.9%. These results are in coherence with the studies performed in the past [120], [124]. As such, pulsed LED with 1000 Hz frequency appears to be the most energy-efficient treatment among the rest for cultivating lettuce in an NFT-based hydroponic system within an aquaponics facility or a closed plant production system.

4.7. Conclusion

This chapter is an attempt to compare the energy-use efficiency of *Lactuca sativa L.* (Little gem) plantation in different hydroponic settings. The first part of this chapter tries to evaluate the EUE of lettuce plantation in nutrient film technique (NFT) and deep-water culture (DWC) based hydroponic systems for an aquaponics facility in an indoor controlled environment. Both NFT and DWC-based hydroponic systems offer several advantages over the traditional agricultural practices but differ significantly in their energy footprint. The first experiment involves forty healthy lettuce seedlings that are divided into NFT and DWC hydroponic systems and irradiated with continuous light-emitting diode (LED) irradiance having a photosynthetic photon flux (PPF) of 200 μmol·s-1 and a photoperiod of 16-hours for five weeks. Throughout the crop cycle, energy consumption for artificial illuminance and mechanical pumps is logged on a cloud platform. Upon harvesting, lettuce growth characteristics such as fresh plant weight, shoot and root weight, plant height, root length, and the number of leaves is recorded and used to compute the energy-use efficiency of the two hydroponic systems. Based on the results from the first experiment, NFT-grown hydroponic lettuce is found to offer 27.7% better energy-use efficiency as compared to the DWC system, which can be attributed to better nutrient flow and optimized plant density deployed in the NFT hydroponic system.

These results are carried forth for the second set of experiments, which involves evaluating the energy-use efficiency for lettuce plantation under an NFT-based hydroponic system using pulsed and continuous LED artificial illuminance, eventually facilitating the design, selection, and implementation of a hydroponic component of indoor aquaponics facility. The experimental setup involves 20 healthy lettuce seedlings placed in three NFT phases each. These phases are irradiated with light-emitting diode (LED), having a varying recipe for a photoperiod of 16-hours for five weeks. Phases 1 and 2 employ pulsed LED irradiance with a duty cycle of 75% and frequency of 500 and 1000 Hz, respectively. With continuous LED irradiation, phase 3 acts as a control. Throughout the growth stage, data related to energy consumption and other important parameters is recorded and logged on a cloud platform to make the study commensurable. Upon harvesting, lettuce growth characteristics such as fresh plant weight, shoot and root weight, plant height, root length, and the number of leaves is recorded and used to compute the energy-use efficiency for different light recipes. Based on the results, pulsed LED irradiation with a duty cycle of 75% and frequency of 1000 Hz (phase 2) offers 8.9% better energy-use efficiency when compared to continuous LED illuminance.

Indoor hydroponic systems are energy-intense, which makes it important to apply techniques, methods, and technology that make the large-scale implementation of such systems feasible. One way of achieving this is to ensure an energy-efficient system such as the NFT is employed and pulsed LED illumination with the right parameters is implemented, providing an economically viable option to the agro-industrial sector. This chapter concludes by recommending a nutrient film technique hydroponic system that utilizes pulsed LED irradiation with a duty cycle of 75% and a frequency of 1000 Hz for an energy-efficient indoor hydroponic lettuce plantation.

Chapter 5 Conclusion

5.1. General Conclusion

Resource scarcity has been exacerbated by unsustainable urban population growth. Traditional farming practices seem vulnerable to matching the growing urban nutritional needs. Furthermore, the environmental footprint of such farming practices, including excess resource utilization, use of pesticides and fertilizers, high energy consumption in the form of transportation and waste processing, and increased water consumption, call for a sustainable food production system. Indoor hydroponics, a class of horticulture that involves cultivating plants by subjecting their bare roots to a nutrient-rich solution, is distinguished as an engineered way of vegetation. Being highly resource and water-efficient, such systems can be operated in dense urban areas as well as in extreme weather conditions. Furthermore, hydroponics can also be integrated with aquaculture, collectively termed aquaponics. Imitating natural cycle, aquaponics presents a symbiotic relationship between plant cultivation and fish farming and thus promotes resource efficiency and sustainability. However, such systems are energy-intense and thus call for techniques, methods, and new technologies that can make their large-scale implementation feasible [129], [130].

This thesis attempts to unify various findings in the field of energy-efficient indoor hydroponics and aquaponics and can be divided into three phases. The first phase involved detailed analysis and review of the present literature on the energy efficiency in the illumination of plant growing compartments in indoor aquaponics. It was found that light-emitting diodes offer significant advantages over other existing alternative illumination sources, such as 75% higher energy-use efficiency, 50% light conversion in the photosynthetically active region, better economics due to reduced operational costs, and long-lasting service period while also offering the robustness of tailoring radiation based on specific plant needs and growth stages. The second stage of this research focused on developing an ontology knowledge model that defined complex and heterogenous relationships between various entities of indoor aquaponics facility. Relevant system knowledge pertaining to energy consumption identified through the literature review was also incorporated into this model. This knowledge was made visually available through an interactive graphical user interface with data populated from the ontology model, providing a step-by-step guide on designing an energy-efficient indoor hydroponic and aquaponic system. The formative assessment performed at AllFactory, University of Alberta, demonstrated the usefulness of this framework. The final phase was divided into two experiments; the first one compared the energy-use efficiency for *Lactuca sativa L.* (Little Gem) plantation under two different hydroponics systems, namely nutrient film technique (NFT) and deep-water culture (DWC). It was found that NFT-grown hydroponic lettuce offered 27.7% better energy-use efficiency as compared to DWC-grown hydroponic lettuce. These results were carried forward to the next experiment, which evaluated the energy-use efficiency of *Lactuca Sativa L.* (Little Gem) plantation-grown within an NFT hydroponics system under varying artificial illumination conditions. Based on the experimental results, pulsed LED illuminance with a frequency of 1000 Hz and a duty cycle of 75% offered 8.9% better energy-use efficiency as compared to continuous LED illuminance.

This research presents an energy-efficient framework for the agro-industrial sector to consider the large-scale implementation of indoor hydroponics and aquaponics system. The ontology knowledge model developed presents an opportunity for individuals to regain cultural and horticulture knowledge while bringing them in greater contact with the process and food source. The community can benefit from this project as it will help drive consumers' awareness of leafy green plant species, showcasing planting knowledge and nurturing consumers' habits in energy-efficient indoor hydroponics and aquaponics farming, a sustainable and green food production system.

5.2. Research Contribution

The contributions of this research can be summarized as follows:

- Identification of energy demand and the characteristics related to artificial illuminance for indoor hydroponic and aquaponic facilities.
  - ✓ Types of artificial lighting
  - ✓ Specific wavelength for enhanced plant growth
  - ✓ Recommended light photoperiod
  - ✓ Daily light integral and photosynthetic photon flux density
- Development of aquaponics ontology model with relevant system knowledge pertaining to energy consumption, artificial illuminance, and environmental parameters, along with other domains.
- Designing a graphical user interface to visualize ontology and provide a step-by-step guide on establishing an energy-efficient indoor hydroponic and aquaponic system.
- Experimental results facilitate the selection of different types of hydroponic components within aquaponics facilities.
- Experimental results are facilitating the implementation of artificial illumination in plant growing compartments of indoor aquaponics.

5.3. Research Limitations

This research is subject to the following limitations:

- The literature review is performed using the PRISMA approach, an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. This method permits replication of review and structures the analysis to allow users to assess its strength and weakness. However, such an approach may include the risk of selection bias or selective outcome reporting.
- AquaONT ontology model and the subsequent graphical user interface is validated in AllFactory, a Learning Factory for training students on the transdisciplinary nature of engineering sciences. Therefore, a practical industrial case study will be more advantageous.
- The experiments comparing the energy-use efficiency of lettuce plantations under varying hydroponics conditions are performed within the aquaponics facility. The facility employs a decoupled aquaponics system resulting in a separate hydroponic nutrient loop and aquaculture effluent loop. The results of this experiment may vary for a coupled aquaponics system.
- The experiments performed to compare the energy-use efficiency of lettuce under different artificial illumination conditions are restricted to a frequency of 500 and 1000 Hz, apart from the control (continuous LED illuminance). The experiment does not take into consideration the red:blue ratio of the wavelengths.
- The results validated by the two experiments are limited to a sample size of 20 lettuce plants. A higher sample size with repeated growth cycles will enhance the accuracy of the conclusion.

5.4. Future Research

- Ontology modelling is a continuous process of building a semantic trajectory. Future work involves updating the AquaONT ontology model as more knowledge on energy-efficient indoor hydroponics and aquaponics becomes available through research and large-scale implementation of this technology.
- Integrating the concept of a digital twin to have a concreate realization of physical entities in the virtual environment, enabling a better understanding of indoor aquaponics system.
- Integrating real-time energy monitoring and control with the interactive platform using the already installed intelligent sensors and the Internet of Things (IoT) devices enhances the user experience and comprehension regarding energy-efficient aquaponics operation.
- Use of image processing to predict growth rate and energy-use efficiency of the hydroponic plantation, allowing the user to alter the environmental conditions to ensure maximum efficiency and yield at a minimum energy cost.
- Broadening the scope of current research by incorporating aquaculture along with hydroponics, collectively analyzing the energy-use efficiency of indoor aquaponics facilities and thus facilitating the large-scale commercial implementation of this sustainable food production system.

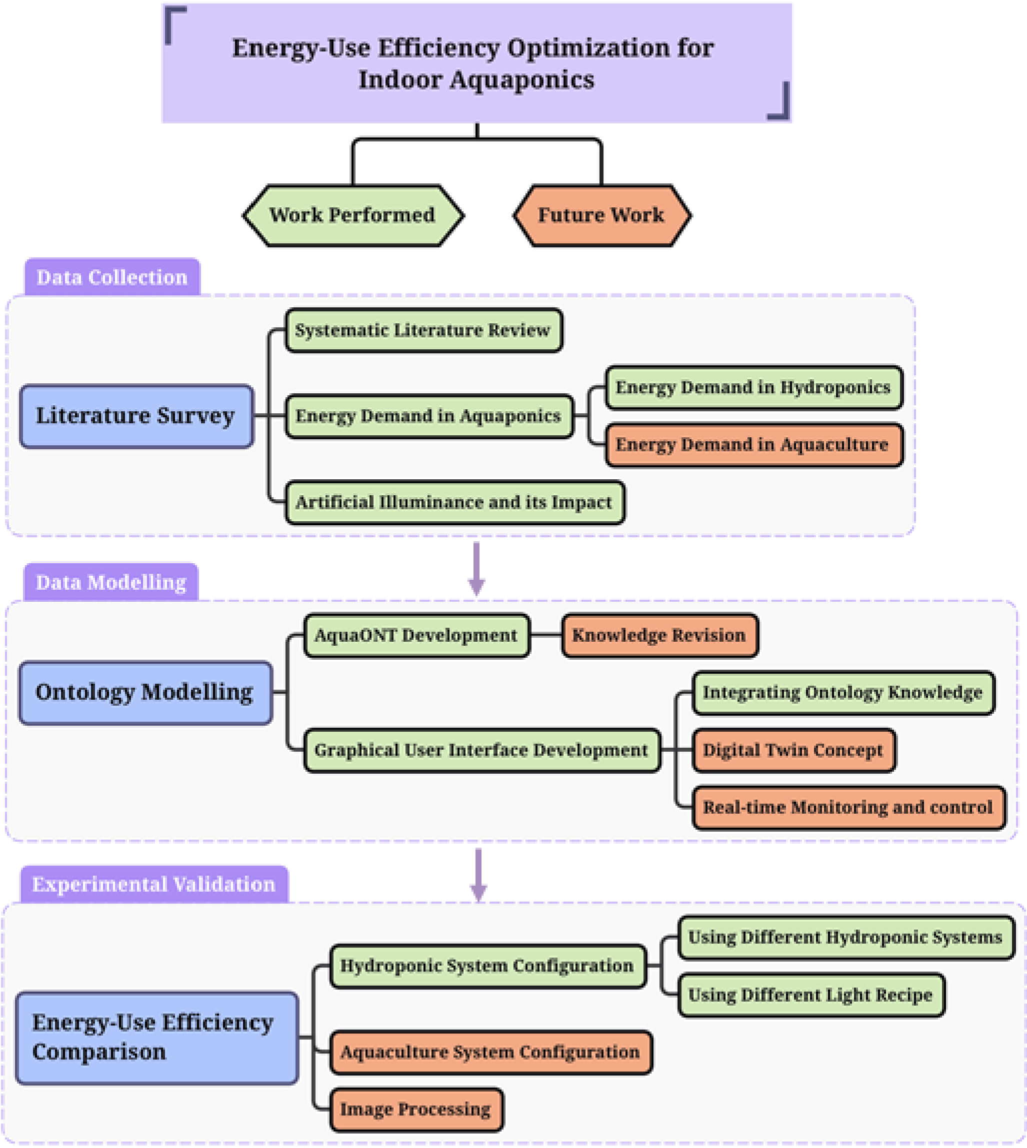

Figure 5-1 Future Work map

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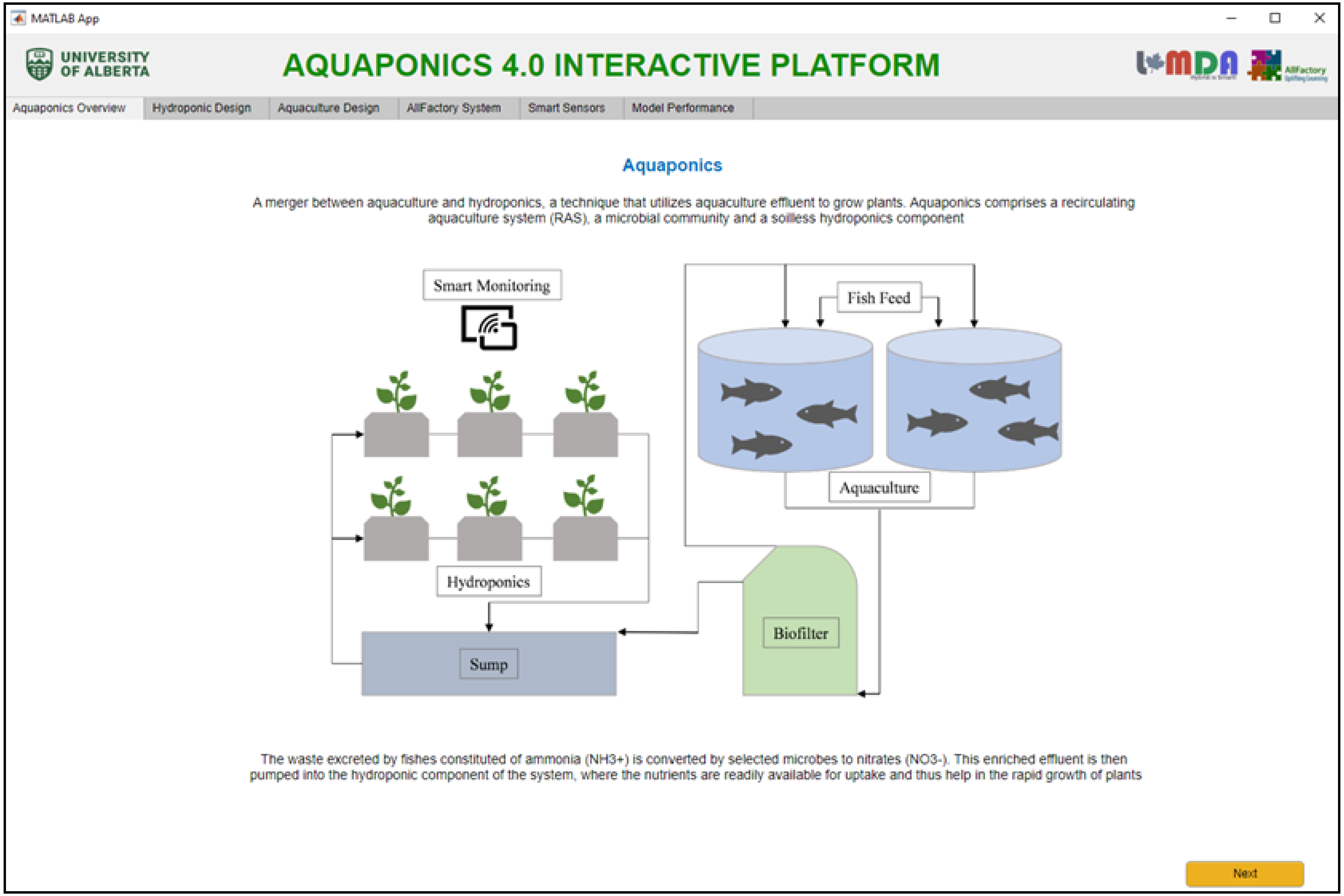
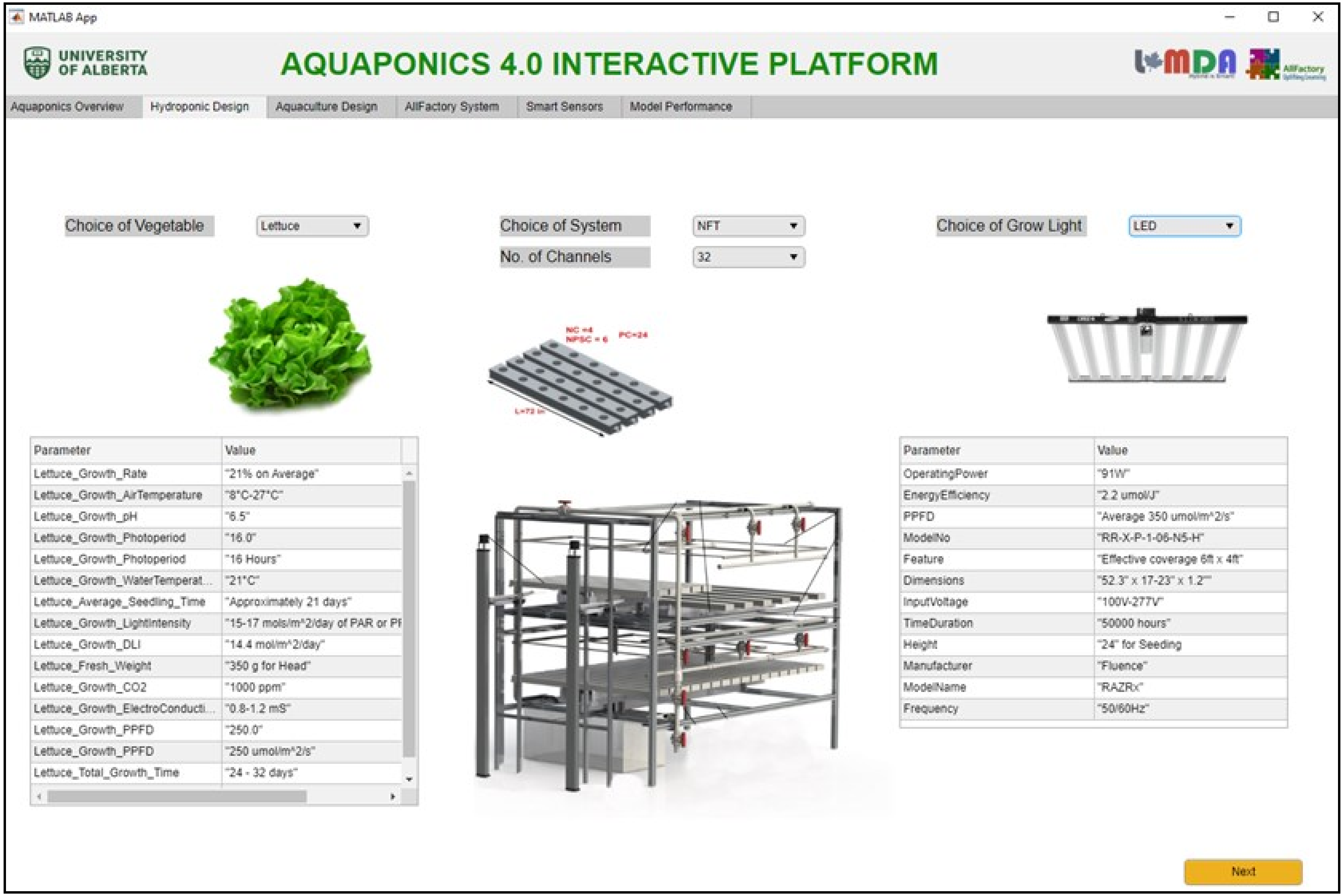
Appendices

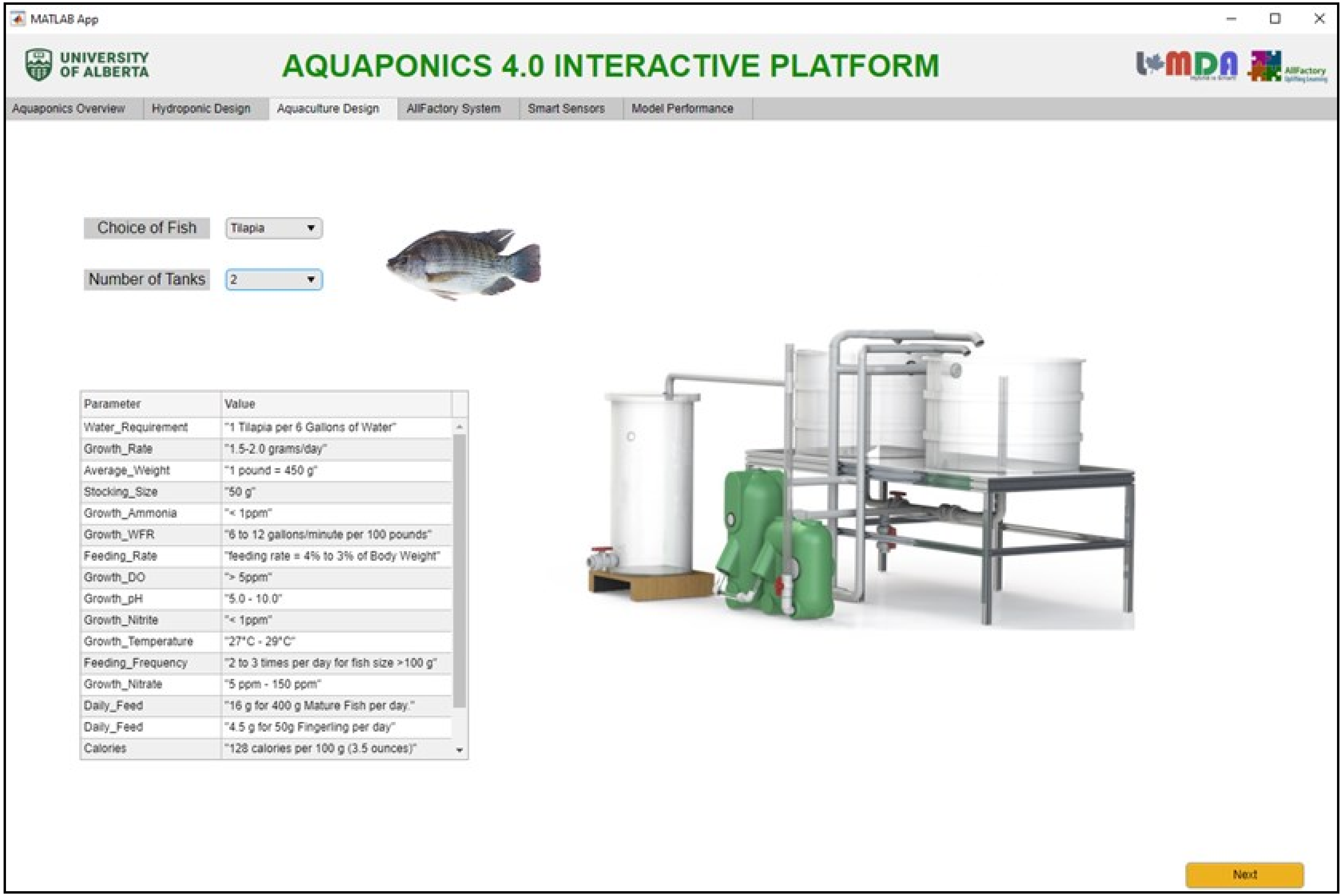
1. AllFactory 4.0 Interactive Platform

The Aquaponics 4.0 graphical user interface platform provides a digital interactive learning approach to design energy-efficient hydroponic and aquaculture components to investigate Aquaponics 4.0 systems. Knowledge from the ontology model is retrieved using SPARQL query engine and is represented using a graphical user interface (GUI). This GUI is designed using the MATLAB app designer tool and allows the user to make choices that eventually impact the model performance and energy-use efficiency.

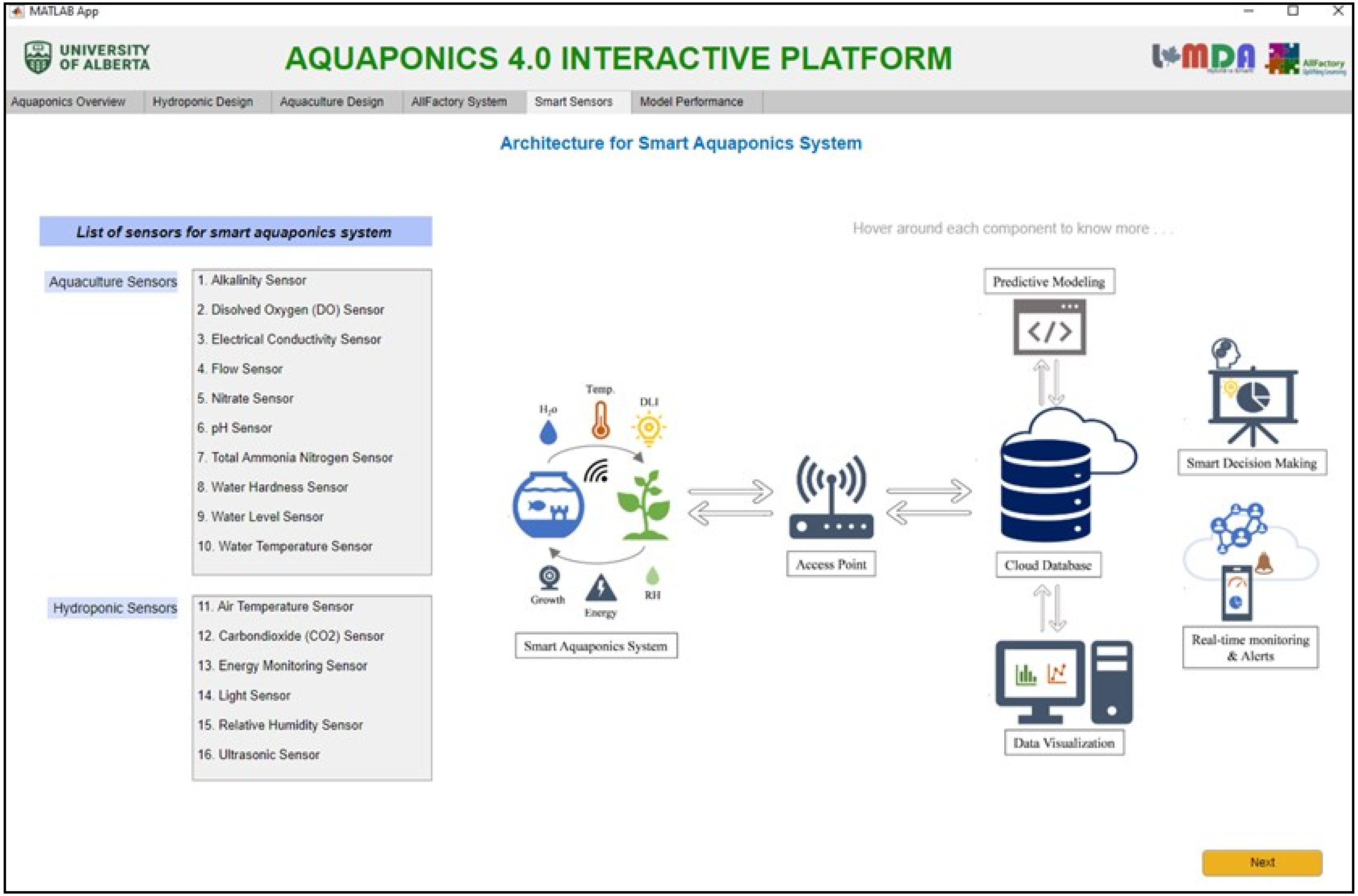
The GUI consists of six tabs, each capturing data from the ontology model and enhancing the user's experience. These tabs have been labeled as: 1) Aquaponics Overview, 2) Hydroponic Design, 3) Aquaculture Design, 4) AllFactory System, 5) Smart Sensors, and 6) Model Performance, and have been shown in the pictures attached to the appendices.

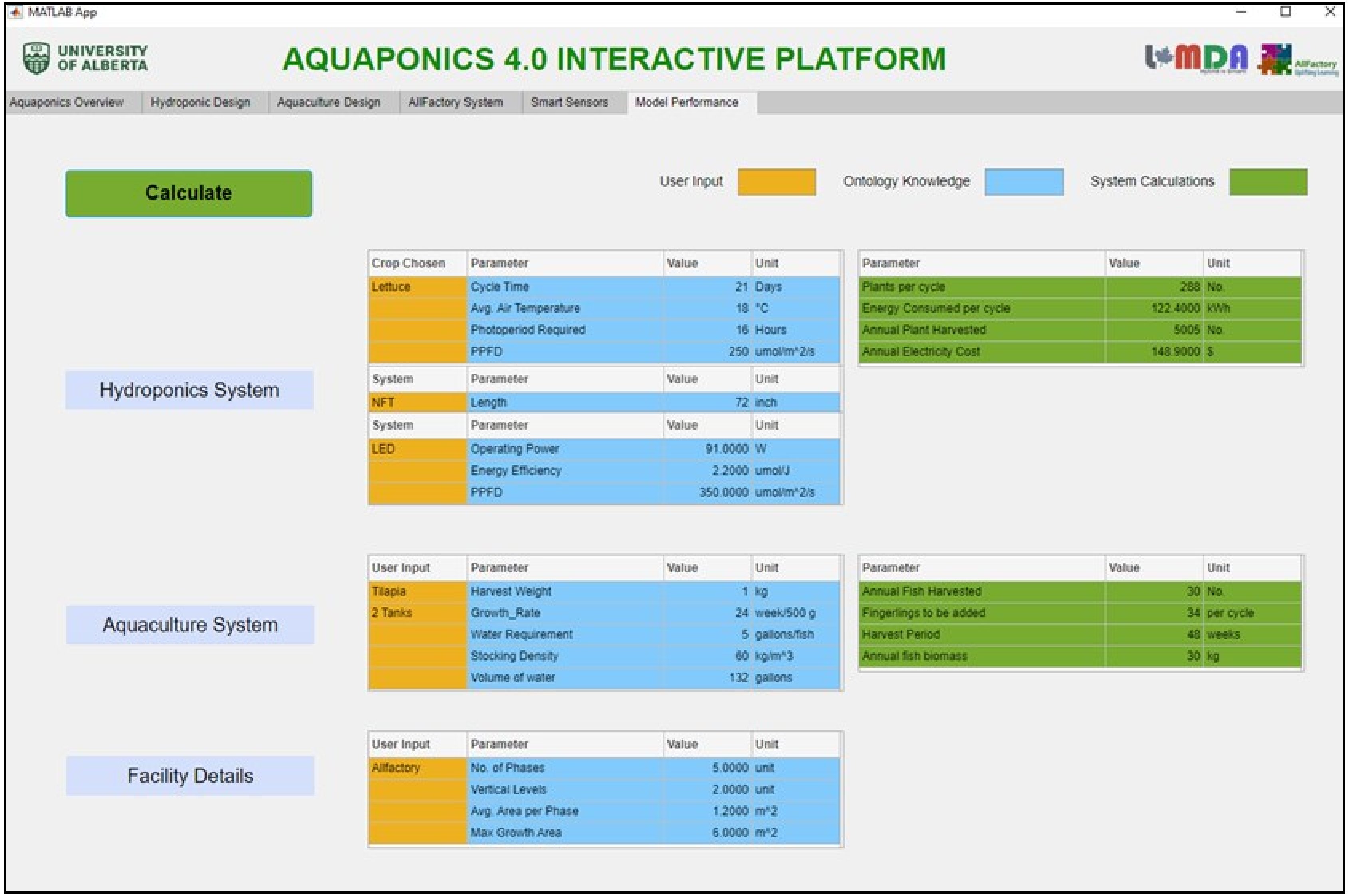

MATLAB App
UNIVERSITY OF ALBERTA
AQUAPONICS 4.0 INTERACTIVE PLATFORM
AllFactory
Aquaponics Overview
Hydroponic Design
Aquaculture Design
AllFactory System
Smart Sensors
Model Performance
Aquaponics
A merger between aquaculture and hydroponics, a technique that utilizes aquaculture effluent to grow plants. Aquaponics comprises a recirculating aquaculture system (RAS), a microbial community and a soilless hydroponics component
Smart Monitoring
Fish Feed
Aquaculture
Hydroponics
Biofilter
Sump
The waste excreted by fishes constituted of ammonia (NH3+) is converted by selected microbes to nitrates (NO3-). This enriched effluent is then pumped into the hydroponic component of the system, where the nutrients are readily available for uptake and thus help in the rapid growth of plants
Next


MATLAB App
UNIVERSITY OF ALBERTA
AQUAPONICS 4.0 INTERACTIVE PLATFORM
Aquaponics Overview
Hydroponic Design
Aquaculture Design
AllFactory System
Smart Sensors
Model Performance
Choice of Vegetable
Lettuce
Choice of System
NFT
No. of Channels
32
Choice of Grow Light
LED
NC =4
NPSC = 6
PC=24
L=72 in
Parameter
Value
Lettuce_Growth_Rate
"21% on Average"
Lettuce_Growth_AirTemperature
"8°C-27°C"
Lettuce_Growth_pH
"6.5"
Lettuce_Growth_Photoperiod
"16.0"
Lettuce_Growth_Photoperiod
"16 Hours"
Lettuce_Growth_WaterTemperat...
"21°C"
Lettuce_Average_Seedling_Time
"Approximately 21 days"
Lettuce_Growth_LightIntensity
"15-17 mols/m^2/day of PAR or PF
Lettuce_Growth_DLI
"14.4 mol/m^2/day"
Lettuce_Fresh_Weight
"350 g for Head"
Lettuce_Growth_CO2
"1000 ppm"
Lettuce_Growth_ElectroConducti...
"0.8-1.2 mS"
Lettuce_Growth_PPFD
"250.0"
Lettuce_Growth_PPFD
"250 umol/m^2/s"
Lettuce_Total_Growth_Time
"24 - 32 days"
Parameter
Value
OperatingPower
"91W"
EnergyEfficiency
"2.2 umol/J"
PPFD
"Average 350 umol/m^2/s"
ModelNo
"RR-X-P-1-06-N5-H"
Feature
"Effective coverage 6ft x 4ft"
Dimensions
"52.3" x 17-23" x 1.2""
InputVoltage
"100V-277V"
TimeDuration
"50000 hours"
Height
"24" for Seeding
Manufacturer
"Fluence"
ModelName
"RAZRx"
Frequency
"50/60Hz"
Next



Parameter	Value
Water_Requirement	"1 Tilapia per 6 Gallons of Water"
Growth_Rate	"1.5-2.0 grams/day"
Average_Weight	"1 pound = 450 g"
Stocking_Size	"50 g"
Growth_Ammonia	"< 1ppm"
Growth_WFR	"6 to 12 gallons/minute per 100 pounds"
Feeding_Rate	"feeding rate = 4% to 3% of Body Weight"
Growth_DO	"> 5ppm"
Growth_pH	"5.0 - 10.0"
Growth_Nitrite	"< 1ppm"
Growth_Temperature	"27°C - 29°C"
Feeding_Frequency	"2 to 3 times per day for fish size >100 g"
Growth_Nitrate	"5 ppm - 150 ppm"
Daily_Feed	"16 g for 400 g Mature Fish per day."
Daily_Feed	"4.5 g for 50g Fingerling per day"
Calories	"128 calories per 100 g (3.5 ounces)"


MATLAB App
UNIVERSITY OF ALBERTA
AQUAPONICS 4.0 INTERACTIVE PLATFORM
Aquaponics Overview
Hydroponic Design
Aquaculture Design
AllFactory System
Smart Sensors
Model Performance
Architecture for Smart Aquaponics System
List of sensors for smart aquaponics system
Aquaculture Sensors
1. Alkalinity Sensor
2. Disolved Oxygen (DO) Sensor
3. Electrical Conductivity Sensor
4. Flow Sensor
5. Nitrate Sensor
6. pH Sensor
7. Total Ammonia Nitrogen Sensor
8. Water Hardness Sensor
9. Water Level Sensor
10. Water Temperature Sensor
Hydroponic Sensors
11. Air Temperature Sensor
12. Carbondioxide (CO2) Sensor
13. Energy Monitoring Sensor
14. Light Sensor
15. Relative Humidity Sensor
16. Ultrasonic Sensor
Hover around each component to know more . . .
Temp.
DLI
Growth
Energy
RH
Smart Aquaponics System
Access Point
Predictive Modeling
Cloud Database
Data Visualization
Smart Decision Making
Real-time monitoring & Alerts
Next


MATLAB App
UNIVERSITY OF ALBERTA
AQUAPONICS 4.0 INTERACTIVE PLATFORM
AllFactory
Aquaponics Overview
Hydroponic Design
Aquaculture Design
AllFactory System
Smart Sensors
Model Performance
Calculate
User Input
Ontology Knowledge
System Calculations
Hydroponics System
Crop Chosen | Parameter | Value | Unit
Lettuce | Cycle Time | 21 | Days
Avg. Air Temperature | 18 | °C
Photoperiod Required | 16 | Hours
PPFD | 250 | umol/m^2/s
System | Parameter | Value | Unit
NFT | Length | 72 | inch
System | Parameter | Value | Unit
LED | Operating Power | 91.0000 | W
Energy Efficiency | 2.2000 | umol/J
PPFD | 350.0000 | umol/m^2/s
Parameter | Value | Unit
Plants per cycle | 288 | No.
Energy Consumed per cycle | 122.4000 | kWh
Annual Plant Harvested | 5005 | No.
Annual Electricity Cost | 148.9000 | $
Aquaculture System
User Input | Parameter | Value | Unit
Tilapia | Harvest Weight | 1 | kg
2 Tanks | Growth_Rate | 24 | week/500 g
Water Requirement | 5 | gallons/fish
Stocking Density | 60 | kg/m^3
Volume of water | 132 | gallons
Parameter | Value | Unit
Annual Fish Harvested | 30 | No.
Fingerlings to be added | 34 | per cycle
Harvest Period | 48 | weeks
Annual fish biomass | 30 | kg
Facility Details
User Input | Parameter | Value | Unit
Allfactory | No. of Phases | 5.0000 | unit
Vertical Levels | 2.0000 | unit
Avg. Area per Phase | 1.2000 | m^2
Max Growth Area | 6.0000 | m^2

2. Growth Characteristics of *Lactuca sativa L.* (Little Gem) plantation

	S. No	Plant Weight [g]	Leaf Weight [g]	Root Weight [g]	Leaf Height [cm]	Root Height [cm]	Total Height [cm]	Plant Width [cm]	No. Of Leaves
PHASE 1	1	24.7	15.2	9.5	10.0	34.0	44.0	10.0	7.0
	2	24.2	16.6	7.6	10.5	33.0	43.5	12.0	10.0
	3	24.1	17.0	7.1	13.0	32.0	45.0	13.0	13.0
	4	30.7	16.9	13.8	13.0	43.0	56.0	11.0	14.0
	5	23.5	16.0	7.5	12.0	29.0	41.0	12.0	13.0
	6	28.9	18.2	10.7	11.0	41.0	52.0	11.0	14.0
	7	29.5	19.9	9.6	13.0	32.0	45.0	15.0	15.0
	8	25.5	16.9	8.6	10.0	28.0	38.0	12.0	14.0
	9	26.8	19.3	7.5	11.0	37.0	48.0	12.0	14.0
	10	33.8	23.2	10.6	9.0	39.0	48.0	15.0	17.0
	11	38.1	25.3	12.8	10.0	34.0	44.0	11.0	13.0
	12	29.1	20.7	8.4	11.0	33.0	44.0	14.0	16.0
	13	34.3	22.0	12.3	12.0	40.0	52.0	14.0	17.0
	14	44.3	27.5	16.8	11.0	40.0	51.0	14.0	19.0
	15	35.5	22.2	13.3	10.0	35.0	45.0	13.0	17.0
	16	34.7	20.1	14.6	12.0	36.0	48.0	10.0	17.0
	17	34.1	22.4	11.7	12.0	32.0	44.0	15.0	16.0
	18	34.6	26.8	7.8	10.0	38.0	48.0	14.0	16.0
	19	30.1	21.0	9.1	11.0	34.0	45.0	17.0	15.0
	20	34.2	24.8	9.4	10.0	37.0	47.0	12.0	17.0
	Total	620.7	412.0	208.7	-	-	-	-	294.0
	Max	44.3	27.5	16.8	13.0	43.0	56.0	17.0	19.0
	Min	23.5	15.2	7.1	9.0	28.0	38.0	10.0	7.0
	Mean	31.0	20.6	10.4	11.1	35.4	46.4	12.9	14.7
	Median	30.4	20.4	9.6	11.0	34.5	45.0	12.5	15.0
	Std Dev	5.3	3.6	2.7	1.1	3.9	4.0	1.8	2.7

	S. No	Plant Weight [g]	Leaf Weight [g]	Root Weight [g]	Leaf Height [cm]	Root Height [cm]	Total Height [cm]	Plant Width [cm]	No. Of Leaves
PHASE 2	1	53.1	38.2	14.9	12.0	28.0	40.0	17.0	26.0
	2	42.8	28.9	13.9	11.0	36.0	47.0	16.0	25.0
	3	77.6	59.6	18.0	11.0	52.0	63.0	17.0	28.0
	4	53.8	41.2	12.6	10.0	39.0	49.0	14.0	20.0
	5	45.6	32.1	13.5	10.0	25.0	35.0	12.0	19.0
	6	59.6	44.6	15.0	11.0	42.0	53.0	12.0	23.0
	7	64.2	46.8	17.4	12.0	41.0	53.0	13.0	24.0
	8	75.1	58.1	17.0	11.0	42.0	53.0	14.0	25.0
	9	53.2	41.8	11.4	10.0	43.0	53.0	11.0	22.0
	10	42.6	25.8	16.8	10.0	32.0	42.0	11.0	18.0
	11	48.5	28.9	19.6	11.0	34.0	45.0	12.0	17.0
	12	71.3	58.1	13.2	11.0	41.0	52.0	14.0	25.0
	13	55.2	42.1	13.1	10.0	40.0	50.0	13.0	21.0
	14	47.2	33.5	13.7	11.0	29.0	40.0	12.0	21.0
	15	52.3	41.0	11.3	11.0	38.0	49.0	12.0	24.0
	16	61.2	47.2	14.0	12.0	38.0	50.0	13.0	25.0
	17	53.9	40.2	13.7	10.0	40.0	50.0	11.0	23.0
	18	42.8	26.8	16.0	10.0	35.0	45.0	11.0	19.0
	19	48.5	32.5	16.0	11.0	35.0	46.0	12.0	18.0
	20	52.1	39.2	12.9	11.0	32.0	43.0	13.0	21.0
	Total	1100.6	806.6	294.0	-	-	-	-	444.0
	Max	77.6	59.6	19.6	12.0	52.0	63.0	17.0	28.0
	Min	42.6	25.8	11.3	10.0	25.0	35.0	11.0	17.0
	Mean	55.0	40.3	14.7	10.8	37.1	47.9	13.0	22.2
	Median	53.2	40.6	14.0	11.0	38.0	49.0	12.5	22.5
	Std Dev	10.1	9.9	2.2	0.7	6.0	6.1	1.8	3.0

	S. No	Plant Weight [g]	Leaf Weight [g]	Root Weight [g]	Leaf Height [cm]	Root Height [cm]	Total Height [cm]	Plant Width [cm]	No. Of Leaves
PHASE 3	1	53.9	38.9	15.0	10.0	32.0	42.0	15.0	23.0
	2	61.6	49.7	11.9	12.0	43.0	55.0	14.0	25.0
	3	77.3	60.2	17.1	12.0	41.0	53.0	15.0	28.0
	4	58.3	43.9	14.4	11.0	40.0	51.0	14.0	23.0
	5	43.1	33.8	9.3	11.0	29.0	40.0	12.0	20.0
	6	60.9	45.2	15.7	11.0	40.0	51.0	12.0	23.0
	7	63.1	47.2	15.9	12.0	40.0	52.0	13.0	24.0
	8	70.1	55.3	14.8	12.0	43.0	55.0	14.0	26.0
	9	64.5	54.2	10.3	12.0	43.0	55.0	14.0	27.0
	10	51.3	39.5	11.8	11.0	35.0	46.0	14.0	21.0
	11	48.5	35.9	12.6	11.0	32.0	43.0	13.0	21.0
	12	62.8	48.5	14.3	11.0	40.0	51.0	12.0	25.0
	13	61.5	49.2	12.3	12.0	39.0	51.0	13.0	26.0
	14	59.2	45.8	13.4	11.0	39.0	50.0	12.0	22.0
	15	62.6	52.6	10.0	12.0	41.0	53.0	13.0	25.0
	16	57.9	42.2	15.7	12.0	42.0	54.0	13.0	22.0
	17	54.8	42.6	12.2	11.0	41.0	52.0	12.0	25.0
	18	63.5	52.1	11.4	12.0	35.0	47.0	13.0	24.0
	19	64.7	54.3	10.4	12.0	43.0	55.0	12.0	27.0
	20	57.8	45.2	12.6	11.0	39.0	50.0	12.0	24.0
	Total	1197.4	936.3	261.1	-	-	-	-	481.0
	Max	77.3	60.2	17.1	12.0	43.0	55.0	15.0	28.0
	Min	43.1	33.8	9.3	10.0	29.0	40.0	12.0	20.0
	Mean	59.9	46.8	13.1	11.5	38.9	50.3	13.1	24.1
	Median	61.2	46.5	12.6	11.5	40.0	51.0	13.0	24.0
	Std Dev	7.3	6.7	2.2	0.6	4.0	4.4	1.0	2.1