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Review on Energy Efficient Artificial Illumination in Aquaponics

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ABSTRACT

The world population is facing unprecedented increase and with that arises the need for additional agricultural resources. 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. 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. 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. Almost three-quarters of this energy is consumed by illumination; as such, the detailed focus of this paper has been placed on the growth lights - types, specific wavelengths, photoperiod, daily light integral, and switching frequency. This paper follows a systematic approach to review the current literature on energy efficiency in aquaponics and address research questions about these topics. It is concluded that light emitting diodes with light treatment tailored for specific plant species and growth phase may offer about 75% energy savings when compared to the traditional lighting. 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. In conclusion, combining reduced energy consumption along with increased energy efficiency address both the economic and environmental sustainability of this growing technology.

1. Introduction

1.1. Food Security Crisis

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 (UN, 2019), as compared to the present 7.9 billion figure (Worldometers, 2021). This is bound to place 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 (Fritsche et al., 2015). Additionally, agricultural irrigation is believed to consume 70% of available freshwater resources (Despommier, 2010).

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 and implementing resilient agricultural practices that increase productivity and production while maintaining the ecosystem and fighting against climate change (UN, 2015).

1.2. Sustainable Food Production System

The resource use efficiency poses a major challenge on 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 (Spiertz, 2010). 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 (Mohareb et al., 2017). However, due to the high energy costs associated with the lighting system, there arises a need to offer energy-efficient solutions (Orsini et al., 2020). New forms of urban agricultural systems such as rooftop greenhouses have been developed (Rufí-Salís et al., 2020) but are limited by the economic viability due to the

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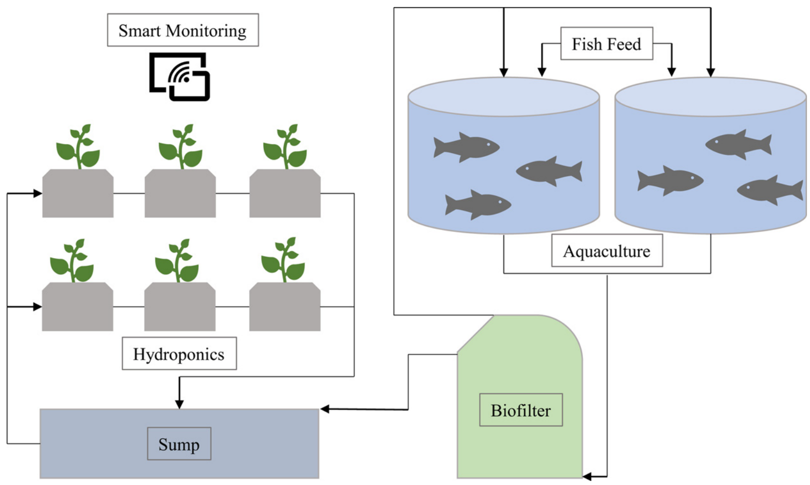

Figure 1. Representation of smart decoupled aquaponics system with NFT grow beds [Adapted from Yanes et al., (2020)]

current building legislation for adapting greenhouse structures (Sanyé-Mengual et al., 2015). At the same time, various solutions to the growing food crisis in the context of sustainability have been proposed in the past (Schröder et al., 2018), a holistic approach to enhancing the 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 (Avgoustaki and Xydis, 2020). 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 (Baganz et al., 2021). Such systems 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 (FAO, 2018).

1.3. Aquaponics – A Resource Efficient Alternative

A plausible alternative to challenges associated with food security lies in the sustainable intensification of agricultural practices around the world, and aquaponics promises to be a technology that has evolved over the recent years to optimize resource use efficiency and maintain the ecosystem balance (Aznar-Sánchez et al., 2020). Aquaponics is defined as a merger between aquaculture and hydroponics, a technique that utilizes aquaculture effluent to grow plants (Yanes et al., 2020). As depicted in Figure 1, aquaponics comprises a recirculating aquaculture system (RAS) and a hydroponics component. The waste excreted by fishes 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 and thus help in the rapid growth of plants. As the waste produced in aquaculture is used as raw input for hydroponics component, aquaponics is adept at emulating natural systems.

Aquaponic systems are more productive annually as they are implacable by seasonal changes and harsh weather conditions. Based on the topology of building enclosure, these systems are generally classified as indoor or greenhouse aquaponics (Proksch et al., 2019). Indoor aquaponic systems require artificial illuminance and active control system for heating, cooling, and ventilation that increase the energy requirements, carbon footprint and the operational cost (Espinal and Matulić, 2019). However, such systems can be operated year-round, in contrast to greenhouse aquaponic facilities that offer commercially feasible operations only in temperate regions with mild winter and summer climate due to their limited environmental control capability (Proksch et al., 2019).

One of the main advantages of an aquaponics system is water efficiency, as 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 closed-loop or coupled aquaponics system and often requires compromises between aquaculture and hydroponics in terms of pH, temperature and nutrient concentration (Espinal and Matulić, 2019). 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 (Blidariu and Grozea, 2011), aquaponics can be considered a high water-efficient system. As summarized by (Maucieri et al., 2018b), aquaponics typically wastes 0.3% to 5% of the system water, mainly in the form of plant transpiration, evaporation losses, scheduled maintenance operations, and fish splashes. 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 (Oliver et al., 2018).

Industry 4.0 has significantly impacted modern agriculture, with smart farming systems becoming more efficient and automatized. Implementation of digital twins that mirror physical entities of automated plant production lines in the virtual world have improved performance of the system (Abbasi et al., 2021b). Monitoring and control of aquaponics have become possible by the integration of the internet of things (IoT) concept, utilizing various sensors and network protocols to gather real-time data regarding important crop, aquatic, and environmental parameters (Bersani et al., 2020). For instance, energy monitoring systems that capture the energy consumption per unit yield have been devised, thus enhancing the efficiency of the process (Odema et al., 2018). Learning factories combining transdisciplinary engineering problems with smart aquaponics have been established to present an effective environment for skills and knowledge development (Martinez and Ahmad, 2021).

1.4. Impediments to Large-scale Aquaponics Implementation

Despite all the advantages of this imminent and growing technology, a few challenges need to be overcome especially when considering its large-scale implementation. There is a significant interdependence among various components within an aquaponic system (Ahmed and Turchini, 2021) and a delicate balance needs to be established among the important parameters for the system to be functional and efficient. It is of paramount importance to ensure that nominal conditions are met for growth and development of all three varieties of organisms that

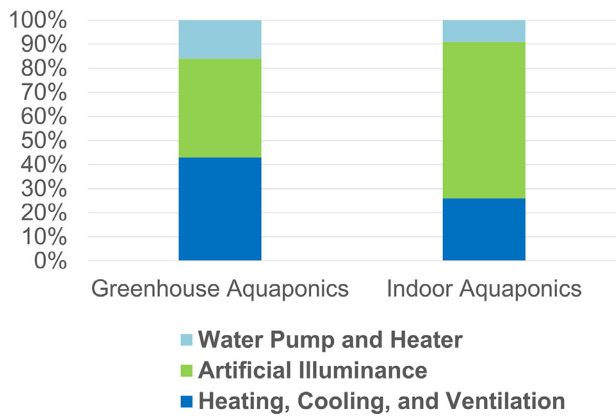

Figure 2. Energy demand and sink for greenhouse and indoor aquaponic system (Chen et al., 2020).

are present in the system - fish, bacteria, and plants. Some of the 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 among others (A. Reyes-Yanes et al., 2020).

Aquaponics in rural and peri-urban context perform differently than ones in urban conditions, primarily due to economic viability, environmental sustainability, and level of technical environmental control (Proksch et al., 2019). Being a land-efficient production system, aquaponics offers advantages in land-scarce urban regions with high property cost and far greater population density. Perpetually witnessing high food demands, operating aquaponics facility in such regions may reduce the transportation cost and other aspects related to supply chain management (Oliver et al., 2018). Rural and peri-urban regions with comparatively low land price that lack any site-specific superiority such as renewable energy sources, waste energy supply, etc, offer inadequate incentives (Turnšek et al., 2019).

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 (Forchino et al., 2017), hydroponic components (Abbasi et al., 2021a; Yang and Kim, 2020), variety of species (Bosma et al., 2017; Knaus and Palm, 2017; Love et al., 2015), management practices (Ghamkhar et al., 2020; König et al., 2018; Maucieri et al., 2018a; Pringle et al., 2017; Tyson et al., 2011), environmental considerations (Fang et al., 2017; Yogev and Gross, 2019; Zhang et al., 2020) and energy efficiency (Kikuchi et al., 2018; Silva et al., 2018). 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 (Goddek et al., 2015; Yep and Zheng, 2019) 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 facility, a recent study highlights electricity as the dominant contributor to all environmental impact categories (Chen et al., 2020). The result from this study is featured in Figure 2. However, indoor growing spaces rely exclusively on artificial illuminance and require less insulation when compared to greenhouses, and as such consume higher portion of electricity for lighting (Proksch et al., 2019). Artificial illuminance alone accounts for an estimated 65% of the total energy consumed by indoor aquaponics (Avgoustaki et al., 2020; Graamans et al., 2020). Furthermore, artificial lighting, which provides the energy required to carry out photosynthesis - a photochemical reaction occurring within plant cells converting atmospheric CO_2 to carbohydrate, contributes to 20-30% of the total production cost associated with indoor farming (Singh et al., 2015). As such, numerous reports on specific concepts related to energy efficiencies, such as the efficiency of various lighting sources (Martineau et al., 2012), the effect of photoperiod and daily light integrals (Zheng et al., 2019), LED red:blue wavelength ratio (Yan et al., 2020), and switching frequency (Olvera-Gonzalez et al., 2021a), 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 a need to present a more holistic approach towards artificial illuminance energy management of large-scale aquaponics and provide a literature review on this particular topic of interest. This study attempts to unite these findings and draw relevant conclusions regarding the energy use efficiency that are essential for the longevity, economics and sustainability of aquaponics.

2. 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.

2.1. Review Protocol

A review protocol provides a concise strategy to be used in the literature review. As such, this paper 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.

2.1.1. 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 specific wavelength promote growth and development of plants whilst minimizing the 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 How have the recent developments in IoT and automation impacted the energy-use efficiency of aquaponics?
6 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?

2.1.2. 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

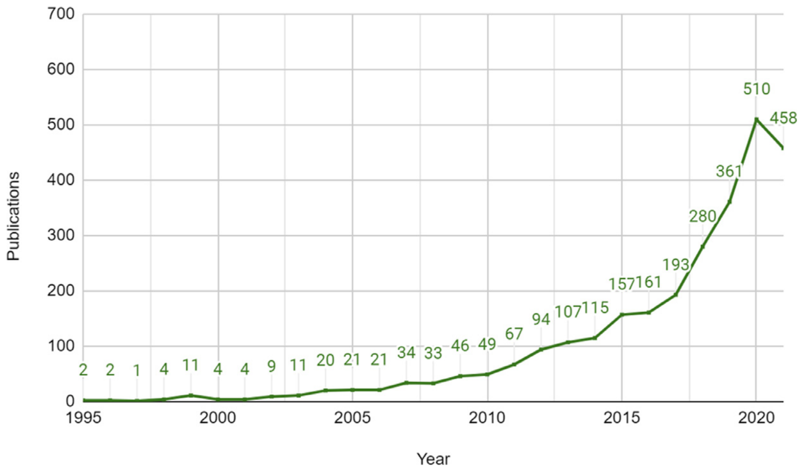

Figure 3. Yearly publication rate obtained from the initial search equation

years of the number of publications obtained through the preliminary search equation is illustrated in Figure 3, 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.

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.

Inclusion criteria:

- 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 article must include the title, year of publication, source, abstract, and DOI.

Exclusion criteria:

- 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.

2.2. 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 4 (Page et al., 2021). 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 on the basis of 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 on the basis of title screening, followed by another 208 records on the basis of abstract screening.
- Eligibility: after the initial articles have been 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 fail to answer the research questions, or the full text was not available.
- Inclusion: the meta-analysis comprises a well-identified and critically evaluated report which is obtained after the inclusion of relevant literature from the previous steps. 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.

3. Results

The systematic literature review yields articles from multiple disciplines, as shown in Figure 5, 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. 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 6.

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

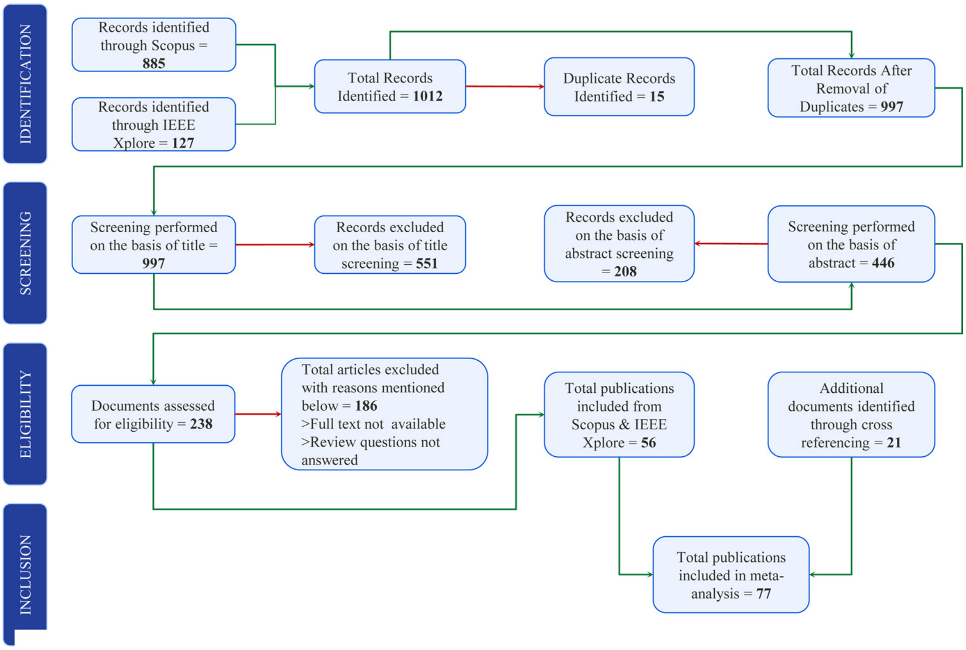

Figure 4. PRISMA approach for record identification [Adapted from Page et al., 2020]

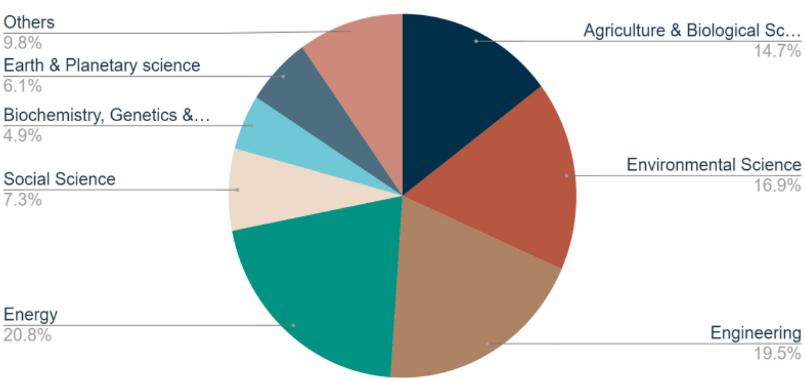

Figure 5. Classification of literature retrieved on the basis of subject area

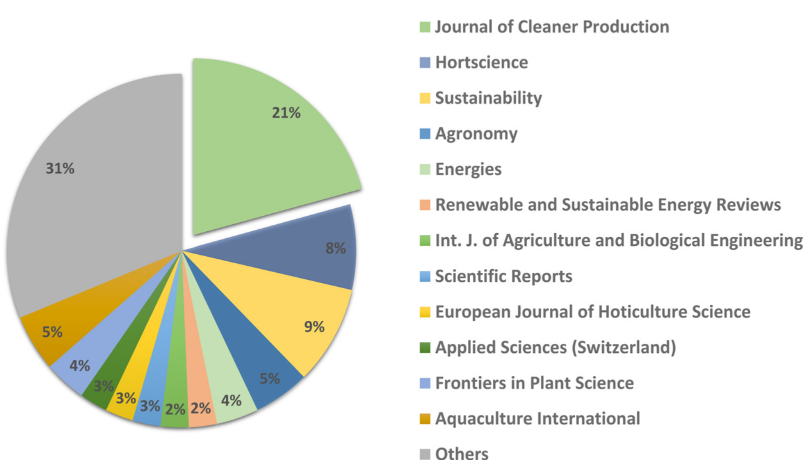

Figure 6. Classification of literature retrieved on the basis of the journal where it is published

lighting sources. These have been elucidated in the sequential sections to follow.

3.1. *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 CO_2 to carbohydrates. Plant photoreceptors absorb the incoming radiation and are responsible for growth, morphology, and photosynthetic efficiency (Chen et al., 2020). 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

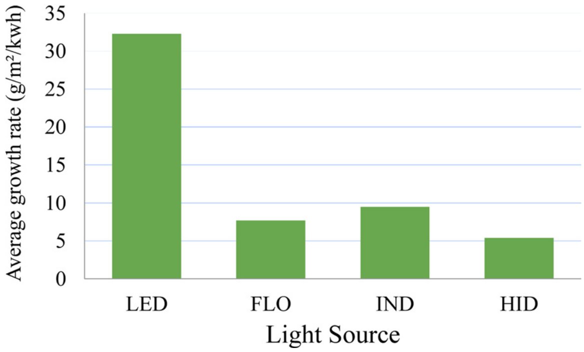

Figure 7. Average growth rate (g/m^2/kwh) for Swiss chard and Beta vulgaris grown under four artificial lighting conditions (Oliver et al., 2018)

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 (Oliver et al., 2018). 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 (Paucek et al., 2020). 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 (Singh et al., 2015). 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 (Martineau et al., 2012). In a separate study, LED systems showed more energy efficiency, with approximately 17% savings when compared to traditional fluorescent lighting (Custódio et al., 2021). Figure 7 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.

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 (Kikuchi et al., 2018). 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 (Xydis et al., 2020).

3.2. 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 (Vitoshkin and Haslavsky, 2020). 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 (Singh et al., 2015). Similar results were obtained by Yan et al. while examining the effect of LED lights with different spectral frequency on the growth of green and purple leaf lettuce cultivars (Yan et al., 2019). Another study tried to quantify the illumination requirements for plant growth by considering the conversion efficiency of electricity to PAR and concluded that LEDs can be adjusted to plants' demand, which can substantially reduce the energy costs (Schmierer et al., 2021). 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.

3.2.1. 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 (Martineau et al., 2012). As an example, the absorption per wavelength by chlorophyll a and chlorophyll b has been illustrated in Figure 8. Singh et al. studied the response of specific wavelengths on 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 1 (Singh et al., 2015). Gomez et al. further added that targeted photomorphogenic, biochemical, or physiological responses could be induced by choosing specific LED wavelengths (Gómez and Izzo, 2018).

3.2.2. 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 varieties 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 (Gao et al., 2020). 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 (Yan et al., 2020). 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 (Jin et al., 2021). 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 (Kong et al., 2019). Table 2 summarizes research conducted on a variety of plant species to study the impact of tailored LED treatments.

3.2.3. 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 (Huber et al., 2021; Yan et al., 2019). 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 (Ohyama et al., 2020). 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 μmol.m^{-2}.s^{-1} (An et al., 2021). Another important parameter significantly effecting the energy-use efficiency in

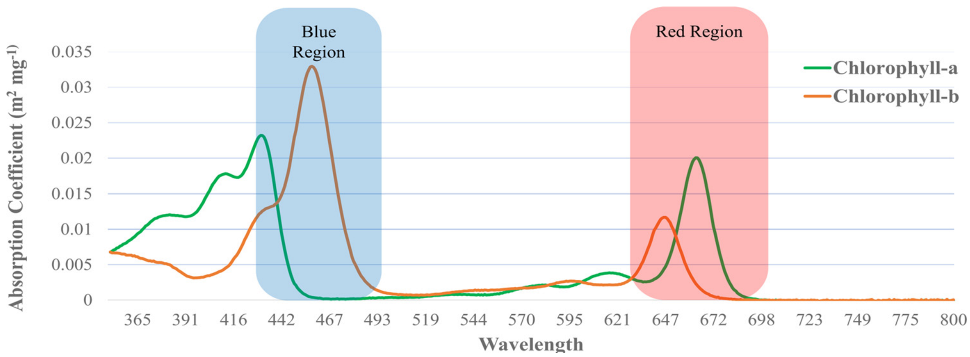

Figure 8. Absorption of Chlorophyll a and b for different wavelength [Adapted from Clementson et al. 2019]

Table 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 colour - 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

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

Reference	Plant Species	Light Treatment	Effect
(Yan et al., 2020)	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.
(Gao et al., 2020)	Spinach *(Spinacia oleracea L.)*	LED with R:B ratio of 1.2	Higher fresh and dry spinach weight, energy yield, and light-use efficiency.
(Hernández et al., 2016)	Tomato *(Solanum lycopersicum)*	LED with R:B ratio of 2.3	39% increase in dry mass and better growing efficacy than fluorescent treatment.
(Chen et al., 2021)	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%).
(Kong et al., 2019)	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.
(Huber et al., 2021)	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.
(Pennisi et al., 2019)	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.
(Yan et al., 2019)	Lettuce *(Lactuca sativa L.)*	LED with R:B ratio of 2.7	Higher fresh leaf yield and improved light-use efficiency.

aquaponics is the photoperiod – amount of time each day during which plants receive illumination in the PAR region (Singh et al., 2015).

Zheng et al. observed a 38.9% increase in number of strawberry *(Fragaria × ananassa)* runner plants as the DLI rose from 8.6 to 11.5 mol.m^{-2}.d^{-1}, while biomass of runner plants and crown diameter showed identical results (Zheng et al., 2019). This study concluded that a daily light integral in the range of 11.5-17.3 mol.m^{-2}.d^{-1} was ideal to improve the strawberry harvest and runner growth for indoor hydroponics system illuminated by LEDs, with 11.5 mol.m^{-2}.d^{-1} providing 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 application of 12.6 mol.m^{-2}.d^{-1} DLI (Yan et al., 2020). Pennisi et al. concluded that an optimal management directive for indoor plantation of leafy vegetables and herbs is

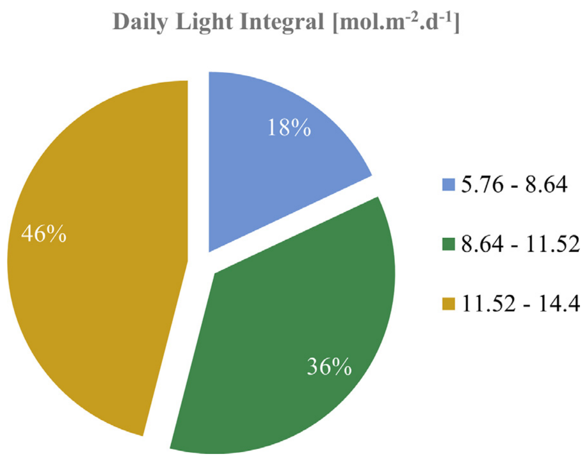

Figure 9. Recommended DLI range in mol.m^{-2}.d^{-1} based on the various literature analyzed.

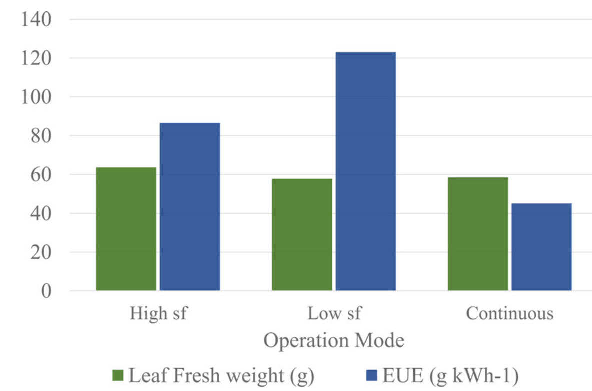

Figure 10. Leaf fresh weight and energy-use efficiency comparison for indoor lettuce plantation in pulsed (high and low switching frequency) and continuous mode (Carotti et al., 2021)

considered to be a 16 h/day photoperiod with a DLI of 14.4 mol.m^{-2}.d^{-1} (Pennisi et al., 2020). Further literature analysed 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 9.

3.3. 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 (Olvera-Gonzalez et al., 2021a). 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 (Harun et al., 2013). 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 net chlorophyll content or quantum yield (ØPSII) (Kanechi et al., 2016). Similar results were obtained by Song et al. while observing the seedling performance during the early photomorphogenic development of sprouts, kale, and beet (Song et al., 2019). 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. modelled 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 implementing pulsed LED lighting with low switching frequency without effecting the plant properties apart from the additional benefits of increased LED lifetime (Olvera-Gonzalez et al., 2021b). Further studies (Avgoustaki et al., 2020; Carotti et al., 2021) have validated the positive impact of pulsed LED treatment on the energy-use efficiency of indoor farming, as presented in Figure 10.

3.4. 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 (Wei et al., 2019). 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 (Islam Sarker et al., 2019). 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 (Wang et al., 2015). 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 (Vernandhes et al., 2018). 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 ChIF sensor(Urschel and Pocock, 2018).

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 (Karimanzira and Rauschenbach, 2019; Odema et al., 2018; Abraham Reyes-Yanes et al., 2020). 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 (Karimanzira et al., 2021; A. Reyes-Yanes et al., 2020).

An architecture for smart aquaponics system has been depicted in Figure 11. It comprises of various different sensors that capture data related to relative humidity, temperature, light intensity, energy consumption, water level and plant growth rate (Witzel et al., 2019). 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 facility manager to monitor and control 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 pattern, 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 stan-

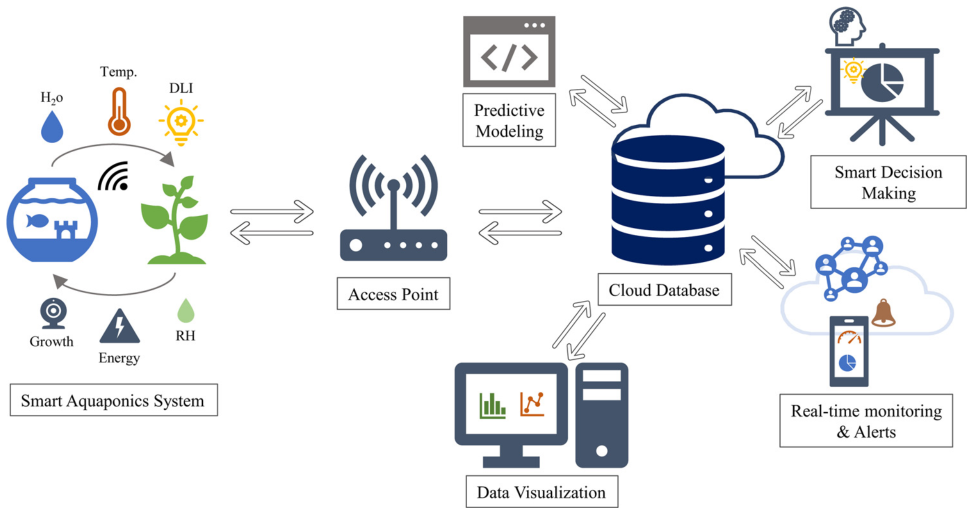

Figure 11. System architecture for smart aquaponics

dards leading to less interoperability among systems. The initial cost for 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.

4. 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 PPFD in the range of 200 – 250 μmol.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 regards 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 analysed, 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.

A number of 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 (Martinez et al., 2020). 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.

5. Conclusions

Increasing contributions in the field of energy-efficient aquaponics are attracting attention from researchers and practitioners, primarily due to its potential of offering sustainable food production system for the growing world population. This paper is an effort to perform analysis and review on the energy efficiency in illumination of plant growing compartments in aquaponics. Various research papers have been analysed 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 treatment 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 plant growth, while a high switching frequency is found to offer about 50% energy savings as compared to continuous operation mode. The paper also discusses the emerging trends of improving 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.

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.clcb.2022.100015.

References

Abbasi, R., Martinez, P., Ahmad, R., 2021a. An ontology model to support the automated design of aquaponic grow beds. Procedia CIRP 100, 55–60. doi:10.1016/j.procir.2021.05.009.

Abbasi, R., Yanes, A.R., Villanuera, E.M., Ahmad, R., 2021b. Real-time Implementation of Digital Twin for Robot Based Production Line. SSRN Electron. J. 4–6. doi:10.2139/ssrn.3860500.

Ahmed, N., Turchini, G.M., 2021. Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. J. Clean. Prod. doi:10.1016/j.jclepro.2021.126604.

An, S., Hwang, H., Chun, C., Jang, Y., Lee, H.J., Wi, S.H., Yeo, K.-H., Yu, I.-H., Kwack, Y., 2021. Evaluation of air temperature, photoperiod and light intensity conditions to produce cucumber scions and rootstocks in a plant factory with artificial lighting. Horticulturae 7. doi:10.3390/horticulturae7050102.

Avgoustaki, D.D., Li, J., Xydis, G., 2020. Basil plants grown under intermittent light stress in a small-scale indoor environment: Introducing energy demand reduction intelligent technologies. Food Control 118, 107389. doi:10.1016/j.foodcont.2020.107389.

Avgoustaki, D.D., Xydis, G., 2020. Indoor vertical farming in the Urban nexus context: Business growth and resource savings. Sustain 12. doi:10.3390/su12051965.

Aznar-Sánchez, J.A., Velasco-Muñoz, J.F., López-Felices, B., Román-Sánchez, I.M., 2020. An analysis of global research trends on greenhouse technology: Towards a sustainable agriculture. Int. J. Environ. Res. Public Health 17. doi:10.3390/ijerph17020664.

Baganz, G.F.M., Junge, R., Portella, M.C., Goddek, S., Keesman, K.J., Daniela Baganz, Staaks, G., Shaw, Christopher, Lohrberg, F., Kloas, Werner, 2021. The aquaponic principle-It is all about coupling. 10.1111/raq.12596

Bersani, C., Ouammi, A., Sacile, R., Zero, E., 2020. Model predictive control of smart greenhouses as the path towards near zero energy consumption. Energies 13. 10.3390/en13143647

Blidariu, F., Grozea, A., 2011. Increasing the economical efficiency and sustainability of indoor fish farming by means of aquaponics. Anim. Sci. Biotechnol. 44, 1–8.

Bosma, R.H., Lacambra, L., Landstra, Y., Perini, C., Poulie, J., Schwaner, M.J., Yin, Y., 2017. The financial feasibility of producing fish and vegetables through aquaponics. Aquac. Eng. 78, 146–154. doi:10.1016/j.aquaeng.2017.07.002.

Carotti, L., Potente, G., Pennisi, G., Ruiz, K.B., Biondi, S., Crepaldi, A., Orsini, F., Gianquinto, G., Antognoni, F., 2021. Pulsed led light: Exploring the balance between energy use and nutraceutical properties in indoor-grown lettuce. Agronomy 11. doi:10.3390/agronomy11061106.

Chen, P., Zhu, G., Kim, H.J., Brown, P.B., Huang, J.Y., 2020. Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States. J. Clean. Prod. 275, 122888. doi:10.1016/j.jclepro.2020.122888.

Chen, X.-L., Li, Y.-L., Wang, L.-C., Guo, W.-Z., 2021. Red and blue wavelengths affect the morphology, energy use efficiency and nutritional content of lettuce (Lactuca sativa L.). Sci. Rep 11. doi:10.1038/s41598-021-87911-7.

Custódio, M., Cartaxana, P., Villasante, S., Calado, R., Lillebø, A.I., 2021. Led lighting and high-density planting enhance the cost-efficiency of halimione portulacoides extraction units for integrated aquaculture. Appl. Sci. 11. doi:10.3390/app11114995.

Despommier, D.D., 2010. The vertical farm : feeding the world in the 21st century. Thomas Dunne Books/St. Martin's Press, New York.

Espinal, C.A., Matulić, D., 2019. Recirculating Aquaculture Technologies, Aquaponics Food Production Systems. 10.1007/978-3-030-15943-6_3

Fang, Y., Hu, Z., Zou, Y., Fan, J., Wang, Q., Zhu, Z., 2017. Increasing economic and environmental benefits of media-based aquaponics through optimizing aeration pattern. J. Clean. Prod. 162, 1111–1117. doi:10.1016/j.jclepro.2017.06.158.

FAO, 2018. Sustainable food systems concept and framework.

Forchino, A.A., Lourguioui, H., Brigolin, D., Pastres, R., 2017. Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA). Aquac. Eng. 77, 80–88. doi:10.1016/j.aquaeng.2017.03.002.

Fritsche, U.R., Laaks, S., Eppler, U., 2015. Urban Food Systems and Global Sustainable Land Use prepared by. Glob. Issue Pap. Prep. by IINAS. doi:10.13140/RG.2.1.3478.9286.

Gao, W., He, D., Ji, F., Zhang, S., Zheng, J., 2020. Effects of Daily Light Integral and LED Spectrum on Growth and Nutritional Quality of Hydroponic Spinach. Agronomy doi:10.3390/agronomy10081082.

Ghamkhar, R., Hartleb, C., Wu, F., Hicks, A., 2020. Life cycle assessment of a cold weather aquaponic food production system. J. Clean. Prod. 244, 118767. doi:10.1016/j.jclepro.2019.118767.

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K.V., Jijakli, H., Thorarinsdottir, R., 2015. Challenges of sustainable and commercial aquaponics. Sustain 7, 4199–4224. doi:10.3390/su7044199.

Gómez, C., Izzo, L.G., 2018. Increasing efficiency of crop production with LEDs. AIMS Agric. Food 3, 135–153. doi:10.3934/agrfood.2018.2.135.

Graamans, L., Tenpierik, M., van den Dobbelsteen, A., Stanghellini, C., 2020. Plant factories: Reducing energy demand at high internal heat loads through façade design. Appl. Energy 262. doi:10.1016/j.apenergy.2020.114544.

Harun, I.D.A.N., Ani, N., Ahmad, R., Azmi, N., 2013. Red and blue LED with pulse lighting control treatment for Brassica chinensis in Indoor farming. 2013 IEEE Conference on Open Systems, ICOS 2013 doi:10.1109/ICOS.2013.6735080.

Hernández, R., Eguchi, T., Deveci, M., Kubota, C., 2016. Tomato seedling physiological responses under different percentages of blue and red photon flux ratios using LEDs and cool white fluorescent lamps. Sci. Hortic. (Amsterdam). 213, 270–280. doi:10.1016/J.SCIENTA.2016.11.005.

Huber, B.M., Louws, F.J., Hernández, R., 2021. Impact of Different Daily Light Integrals and Carbon Dioxide Concentrations on the Growth, Morphology, and Production Efficiency of Tomato Seedlings. Front. Plant Sci. 12. doi:10.3389/fpls.2021.615853.

Islam Sarker, M.N., Wu, M., Chanthamith, B., Yusufzada, S., Li, D., Zhang, J., 2019. Big Data Driven Smart Agriculture: Pathway for Sustainable Development. In: 2019 2nd Int. Conf. Artif. Intell. Big Data, ICAIBD 2019, pp. 60–65. doi:10.1109/ICAIBD.2019.8836982.

Jin, W., Urbina, J.L., Heuvelink, E., Marcelis, L.F.M., 2021. Adding Far-Red to Red-Blue Light-Emitting Diode Light Promotes Yield of Lettuce at Different Planting Densities. Front. Plant Sci. 11. doi:10.3389/fpls.2020.609977.

Kanechi, M., Maekawa, A., Nishida, Y., Miyashita, E., 2016. Effects of pulsed lighting based light-emitting diodes on the growth and photosynthesis of lettuce leaves, in: Acta Horticulturae. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 207-214. 10.17660/ActaHortic.2016.1134.28

Karimanzira, D., Na, C., Hong, M., Wei, Y., 2021. Intelligent Information Management in Aquaponics to Increase Mutual Benefits. Intell. Inf. Manag. 13, 50–69. doi:10.4236/iim.2021.131003.

Karimanzira, D., Rauschenbach, T., 2019. Enhancing aquaponics management with IoT-based Predictive Analytics for efficient information utilization. Inf. Process. Agric. 6, 375–385. doi:10.1016/J.INPA.2018.12.003.

Kikuchi, Y., Kanematsu, Y., Yoshikawa, N., Okubo, T., Takagaki, M., 2018. Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. J. Clean. Prod. 186, 703–717. doi:10.1016/j.jclepro.2018.03.110.

Knaus, U., Palm, H.W., 2017. Effects of the fish species choice on vegetables in aquaponics under spring-summer conditions in northern Germany (Mecklenburg Western Pomerania). Aquaculture 473, 62–73. doi:10.1016/j.aquaculture.2017.01.020.

Kong, Y., Nemali, A., Mitchell, C., Nemali, K., 2019. Spectral quality of light can affect energy consumption and energy-use efficiency of electrical lighting in indoor lettuce farming. HortScience 54, 865–872. doi:10.21273/HORTSCI13834-18.

König, B., Janker, J., Reinhardt, T., Villarroel, M., Junge, R., 2018. Analysis of aquaponics as an emerging technological innovation system. J. Clean. Prod. 180, 232–243. doi:10.1016/j.jclepro.2018.01.037.

Love, D.C., Uhl, M.S., Genello, L., 2015. Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. Aquac. Eng. 68, 19–27. doi:10.1016/j.aquaeng.2015.07.003.

Martineau, V., Lefsrud, M., Naznin, M.T., Kopsell, D.A., 2012. Comparison of light-emitting diode and high-pressure sodium light treatments for hydroponics growth of Boston lettuce. HortScience 47, 477–482. doi:10.21273/hortsci.47.4.477.

Martinez, P., Ahmad, R., 2021. AllFactory: An Aquaponics 4.0 Transdisciplinary Educational and Applied Research Learning Factory at the University of Alberta. SSRN Electron. J. 5–7. doi:10.2139/ssrn.3857901.

Martinez, P., Vargas-Martinez, A., Roman-Flores, A., Ahmad, R., 2020. A science mapping study on learning factories research. Procedia Manuf. 45, 84–89. doi:10.1016/J.PROMFG.2020.04.072.

Maucieri, C., Forchino, A.A., Nicoletto, C., Junge, R., Pastres, R., Sambo, P., Borin, M., 2018a. Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. J. Clean. Prod. 172, 3119–3127. doi:10.1016/j.jclepro.2017.11.097.

Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., Borin, M., 2018b. Hydroponic systems and water management in aquaponics: A review. Ital. J. Agron. 13, 1–11. doi:10.4081/ija.2017.1012.

Mohareb, E., Heller, M., Novak, P., Goldstein, B., Fonoll, X., Raskin, L., 2017. Considerations for reducing food system energy demand while scaling up urban agriculture. Environ. Res. Lett. 12. doi:10.1088/1748-9326/aa889b.

Odema, M., Adly, I., Wahba, A., Ragai, H., 2018. Smart aquaponics system for industrial internet of things (IIoT), Advances in Intelligent Systems and Computing. 10.1007/978-3-319-64861-3_79

Ohyama, K., Yamaguchi, J., Enjoji, A., 2020. Resource utilization efficiencies in a closed system with artificial lighting during continuous lettuce production. Agronomy 10. doi:10.3390/agronomy10050723.

Oliver, L.P., Coyle, S.D., Bright, L.A., Shultz, R.C., Hager, J.V., Tidwell, J.H., 2018. Comparison of Four Artificial Light Technologies for Indoor Aquaponic Production of Swiss Chard, Beta vulgaris, and Kale, Brassica oleracea. J. World Aquac. Soc. 49, 837–844. doi:10.1111/JWAS.12471.

Olvera-Gonzalez, E., Escalante-Garcia, N., Myers, D., Ampim, P., Obeng, E., Alaniz-Lumbreras, D., Castaño, V., 2021a. Pulsed led-lighting as an alternative energy savings technique for vertical farms and plant factories. Energies 14. doi:10.3390/en14061603.

Olvera-Gonzalez, E., Rivera, M.M., Escalante-Garcia, N., Flores-Gallegos, E., 2021b. Modeling energy led light consumption based on an artificial intelligent method applied to closed plant production system. Appl. Sci. 11. doi:10.3390/app11062735.

Orsini, F., Pennisi, G., Zulfiqar, F., Gianquinto, G., 2020. Sustainable use of resources in plant factories with artificial lighting (PFALs). Eur. J. Hortic. Sci. 85, 297–309. doi:10.17660/eJHS.2020/85.5.1.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372. doi:10.1136/bmj.n71, n71.

Paucek, I., Appolloni, E., Pennisi, G., Quaini, S., Gianquinto, G., Orsini, F., 2020. LED lighting systems for horticulture: Business growth and global distribution. Sustain 12. doi:10.3390/su12187516.

Pennisi, G., Blasioli, S., Cellini, A., Maia, L., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernandez, J.A., Stanghellini, C., Orsini, F., Gianquinto, G., 2019. Unraveling the role of red:Blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Front. Plant Sci. 10. doi:10.3389/fpls.2019.00305.

Pennisi, G., Orsini, F., Landolfo, M., Pistillo, A., Crepaldi, A., Nicola, S., Fernández, J.A., Marcelis, L.F.M., Gianquinto, G., 2020. Optimal photoperiod for indoor cultivation of leafy vegetables and herbs. Eur. J. Hortic. Sci. 85, 329–338. doi:10.17660/eJHS.2020/85.5.4.

Pringle, A.M., Handler, R.M., Pearce, J.M., 2017. Aquavoltaics: Synergies for dual use of water area for solar photovoltaic electricity generation and aquaculture. Renew. Sustain. Energy Rev. 80, 572–584. doi:10.1016/j.rser.2017.05.191.

Proksch, G., Ianchenko, A., Kotzen, B., 2019. Aquaponics in the Built Environment, Aquaponics Food Production Systems. 10.1007/978-3-030-15943-6_21

Reyes-Yanes, Abraham, Gelio, S., Martinez, P., Ahmad, R., 2020. Wireless Sensing Module for IoT Aquaponics database construction. In: 8th Int. Conf. Control. Mechatronics Autom. (Manuscript Submitt, 9, pp. 43–47. doi:10.18178/ijeee.9.2.43-47.

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., Parada, F., Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020. Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency? J. Clean. Prod. 261. doi:10.1016/j.jclepro.2020.121213.

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. Int. J. Life Cycle Assess. 20, 350–366. doi:10.1007/s11367-014-0836-9.

Schmierer, M., Brueck, H., Asch, F., Sauerborn, J., 2021. Estimating the quantum requirements for plant growth and related electricity demand for LED lighting systems. J. fur Verbraucherschutz und Leb. 16, 35–43. doi:10.1007/s00003-021-01314-4.

Schröder, P., Beckers, B., Daniels, S., Gnädinger, F., Maestri, E., Marmiroli, N., Mench, M., Millan, R., Obermeier, M.M., Oustriere, N., Persson, T., Poschenrieder, C., Rineau, F., Rutkowska, B., Schmid, T., Szulc, W., Witters, N., Sæbø, A., 2018. Intensify production, transform biomass to energy and novel goods and protect soils in Europe—A vision how to mobilize marginal lands. Sci. Total Environ. 616-617, 1101–1123. doi:10.1016/J.SCITOTENV.2017.10.209.

Silva, L., Valdés-Lozano, D., Escalante, E., Gasca-Leyva, E., 2018. Dynamic root floating technique: An option to reduce electric power consumption in aquaponic systems. J. Clean. Prod. 183, 132–142. doi:10.1016/j.jclepro.2018.02.086.

Singh, D., Basu, C., Meinhardt-Wollweber, M., Roth, B., 2015. LEDs for energy efficient greenhouse lighting. Renew. Sustain. Energy Rev. 49, 139–147. doi:10.1016/J.RSER.2015.04.117.

Song, S., Kusuma, P., Carvalho, S.D., Li, Y., Folta, K.M., 2019. Manipulation of seedling traits with pulsed light in closed controlled environments. Environ. Exp. Bot. 166, 103803. doi:10.1016/J.ENVEXPBOT.2019.103803.

Spiertz, J.H.J., 2010. Nitrogen, sustainable agriculture and food security. A review. Agron. Sustain. Dev. 30, 43–55. doi:10.1051/agro:2008064.

Turnšek, M., Morgenstern, R., Schröter, I., Mergenthaler, M., Hüttel, S., Leyer, M., 2019. Commercial Aquaponics: A Long Road Ahead, Aquaponics Food Production Systems. 10.1007/978-3-030-15943-6_18

Tyson, R.V., Treadwel, D.D., Simonne, E.H., 2011. Opportunities and challenges to sustainability in aquaponic systems. Horttechnology 21, 6–13. doi:10.21273/horttech.21.1.6.

UN, 2019. World Population Prospects 2019.

UN, 2015. Goal 2: Zero Hunger - United Nations Sustainable Development [WWW Document]. URL https://www.un.org/sustainabledevelopment/hunger/(accessed 8.9.21).

Urschel, M.R., Pocock, T., 2018. Remote detection of growth dynamics in red lettuce using a novel chlorophyll a fluorometer. Agronomy 8. doi:10.3390/agronomy8100227.

Vernandhes, W., Salahuddin, N.S., Kowanda, A., Sari, S.P., 2018. Smart aquaponic with monitoring and control system based on IoT. In: Proc. 2nd Int. Conf. Informatics Comput. ICIC 2017 2018-Janua, pp. 1–6. doi:10.1109/IAC.2017.8280590.

Vitoshkin, H., Haslavsky, V., 2020. Thermal analysis and climate control of experimental two level hydroponic growth cell. In: Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering, pp. 1–5. doi:10.11159/htff20.136.

Wang, D., Zhao, J., Huang, L., Xu, D., 2015. Design of A Smart Monitoring and Control System for Aquaponics Based on. In: OpenWrt BT - Proceedings of the 5th International Conference on Information Engineering for Mechanics and Materials. Atlantis Press, pp. 937–942. doi:10.2991/icimm-15.2015.171.

Wei, Y., Li, W., An, D., Li, D., Jiao, Y., Wei, Q., 2019. Equipment and Intelligent Control System in Aquaponics: A Review. IEEE Access 7, 169306–169326. doi:10.1109/ACCESS.2019.2953491.

Witzel, O., Wilm, S., Karimanzira, D., Baganz, D., 2019. Controlling and regulation of integrated aquaponic production systems - An approach for a management execution system (MES). Inf. Process. Agric. 6, 326–334. doi:10.1016/J.INPA.2019.03.007.

Worldometers, 2021. World Population Clock: Worldometer [WWW Document]. URL https://www.worldometers.info/world-population/(accessed 8.9.21).

Xydis, G.A., Liaros, S., Avgoustaki, D.D., 2020. Small scale Plant Factories with Artificial Lighting and wind energy microgeneration: A multiple revenue stream approach. J. Clean. Prod. 255, 120227. doi:10.1016/j.jclepro.2020.120227.

Yan, Z., He, D., Niu, G., Zhou, Q., Qu, Y., 2020. Growth, nutritional quality, and energy use efficiency in two lettuce cultivars as influenced by white plus red versus red plus blue leds. Int. J. Agric. Biol. Eng. 13, 33–40. doi:10.25165/j.ijabe.20201302.5135.

Yan, Z., He, D., Niu, G., Zhou, Q., Qu, Y., 2019. Growth, nutritional quality, and energy use efficiency of hydroponic lettuce as influenced by daily light integrals exposed to white versus white plus red light-emitting diodes. HortScience 54, 1737–1744. doi:10.21273/HORTSCI14236-19.

Yanes, A.R., Martinez, P., Ahmad, R., 2020. Towards automated aquaponics: A review on monitoring, IoT, and smart systems. J. Clean. Prod. 263, 121571. doi:10.1016/J.JCLEPRO.2020.121571.

Yang, T., Kim, H.J., 2020. Comparisons of nitrogen and phosphorus mass balance for tomato-, basil-, and lettuce-based aquaponic and hydroponic systems. J. Clean. Prod. 274, 122619. doi:10.1016/j.jclepro.2020.122619.

Yep, B., Zheng, Y., 2019. Aquaponic trends and challenges - A review. J. Clean. Prod. 228, 1586–1599. doi:10.1016/j.jclepro.2019.04.290.

Yogev, U., Gross, A., 2019. Reducing environmental impact of recirculating aquaculture systems by introducing a novel microaerophilic assimilation reactor: Modeling and proof of concept. J. Clean. Prod. 226, 1042–1050. doi:10.1016/j.jclepro.2019.04.003.

Zhang, H., Gao, Y., Shi, H., Lee, C.T., Hashim, H., Zhang, Z., Wu, W.M., Li, C., 2020. Recovery of nutrients from fish sludge in an aquaponic system using biological aerated filters with ceramsite plus lignocellulosic material media. J. Clean. Prod. 258, 120886. doi:10.1016/j.jclepro.2020.120886.

Zheng, J.F., He, D.X., Ji, F., 2019. Effects of light intensity and photoperiod on runner plant propagation of hydroponic strawberry transplants under LED lighting. Int. J. Agric. Biol. Eng. 12, 26–31. doi:10.25165/j.ijabe.20191206.5265.