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A Forefront Framework for Sustainable Aquaponics Modeling and Design

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Abstract: Aquaponics systems and technologies are growing primary industries in many countries, with high environmental and socio-economic advantages. Aquaponics is a closed-loop system that produces aquatic animals and plants in a new way using recirculated water and nutrients. With a growing world population expected to reach 9.7 billion by 2050, food production sustainability is a primary issue in today's world agenda, and aquaponics and aquaculture systems can be potential contributors to the challenge. Observing the climate changes and global warming's impact on the ecosystem, decreasing aqua animal stocks, and responding to increasing demand are turning points in the sustainability era. In the past 15 years, fish production has doubled, thus denoting that aquaponics transforms into commercial scales with a revolutionized production, high efficiency, and fewer resources' utilization, thus requiring proper operation and management standards and practices. Therefore, this study aims to shape a new framework for sustainable aquaponics modeling and utilization as the all-in-one solution platform covering technical, managerial, socio-economic, institutional, and environmental measures within the suitability requirements. The proposed model in this study offers a systematic approach to the design and implementation of sustainability-efficient aquaponics and aquaculture systems. Through an exhaustive coverage of the topic, this research effort can be counted as a practical reference for researchers, scholars, experts, practitioners, and students in the context of aquaponics and aquaculture studies.

Keywords: aquaponics; aquaculture; aquaponics modeling; aquaponics design; aquaponics sustainability

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1. Introduction

World aquatic industry productions have shown a rapid growth of more than 527% in aquaculture and 14% in fisheries productions from 1990 to 2018 [1]. These figures show an encouraging development of trends of aquaponics and aquaculture systems globally aligned with today's cutting-edge technologies. Meanwhile, aquatic farms' ecological and environmental distresses are a turning point requiring exhaustive measures and even replicating or re-adapting successful policies within the recent constrained environmental disaster. Aquaponics' environmental impact comprises factors that complicate qualitatively constrained airborne and waterborne emissions [2] within the acceptable permitted range for maintaining environmental sustainability in the long run.

With an average annual growth rate of 3.1%, the consumption of fish products has almost doubled compared to annual population growth (1.6%) for the same period between 1961 to 2017 [1]. It increased per capita from 9.0 kg in 1961 to 20.5 kg in 2018 at a rate of 1.5% growth per year [1]. Simultaneously, aquatic plants' production has shown a dramatic shift from 1.7 million tonnes in 1957 [3] to 114.5 million tonnes in 2018 (in live weight) [1]. From 2001–2018, global aquaculture production of farmed aquatic animals has had an annual average growth of 5.3% [1], while among aquaculture production, fish production has doubled in the past 15 years, [4]. This growth rate indicates development trends in aquaponics and aquaculture systems that continue improving technical and technological sustainability and restraining ecosystem distress.

Since aquaponics systems are self-regulating, they have less impact on the ecosystem, as they use limited environmental contents (use of external organics, chemicals, fertilizers, antibiotics, and reducing freshwater consumption and wastewater discharge). According to the report by [4], 70% of the freshwater consumed globally for food production can be saved by 30–70% through the use of efficient irrigation systems and 90% by using aquaponics systems. The findings herein reveal the facts of aquaponics ecosystems as well as their high environmental adaptability. Freshwater fish have contributed to the golobal food security more than any other aquaculture production during the past two decades [5].

Aquaponics systems are flexible and able to be deployed in different places for various purposes, ensuring that architectural schemes and appearance requirements are met. In this way, in addition to the primary purpose, they can add more aesthetic appeal and monetary value than other systems, as shown in Figure 1.

Aquaponics alignt with the sustainable development goal (SDGs):

- SDG2: Zero hunger;
- SDG7: Energy for everyone and clean;
- SDG8: Both job satisfaction and economic growth;
- SDG12: Responsibility to create Responsibility to use;
- SDG14: Protect the richness of the sea.

First, this study assesses these barriers and then provides optimum solutions to fit the problems, confirming well-accepted practices and standards. Many studies related to aquaponics and aquaculture in the context of sustainable modeling and design have been conducted so far by applying various methodologies and from different perspectives. Still, multidimensional studies that cover modeling and design from technical, managerial, business, social, and institutional dimensional are lacking. Therefore, this study tries to deal with the research gap and develop an exhaustive-viable framework for aquaponics/aquaculture modeling and design process. The long-term objective of this research is divided into three segments: to review available researches efforts, to unify and do a comparative analysis of well-known practices, and finally to formalize and model a framework for energy-efficient building using multidisciplinary approaches.

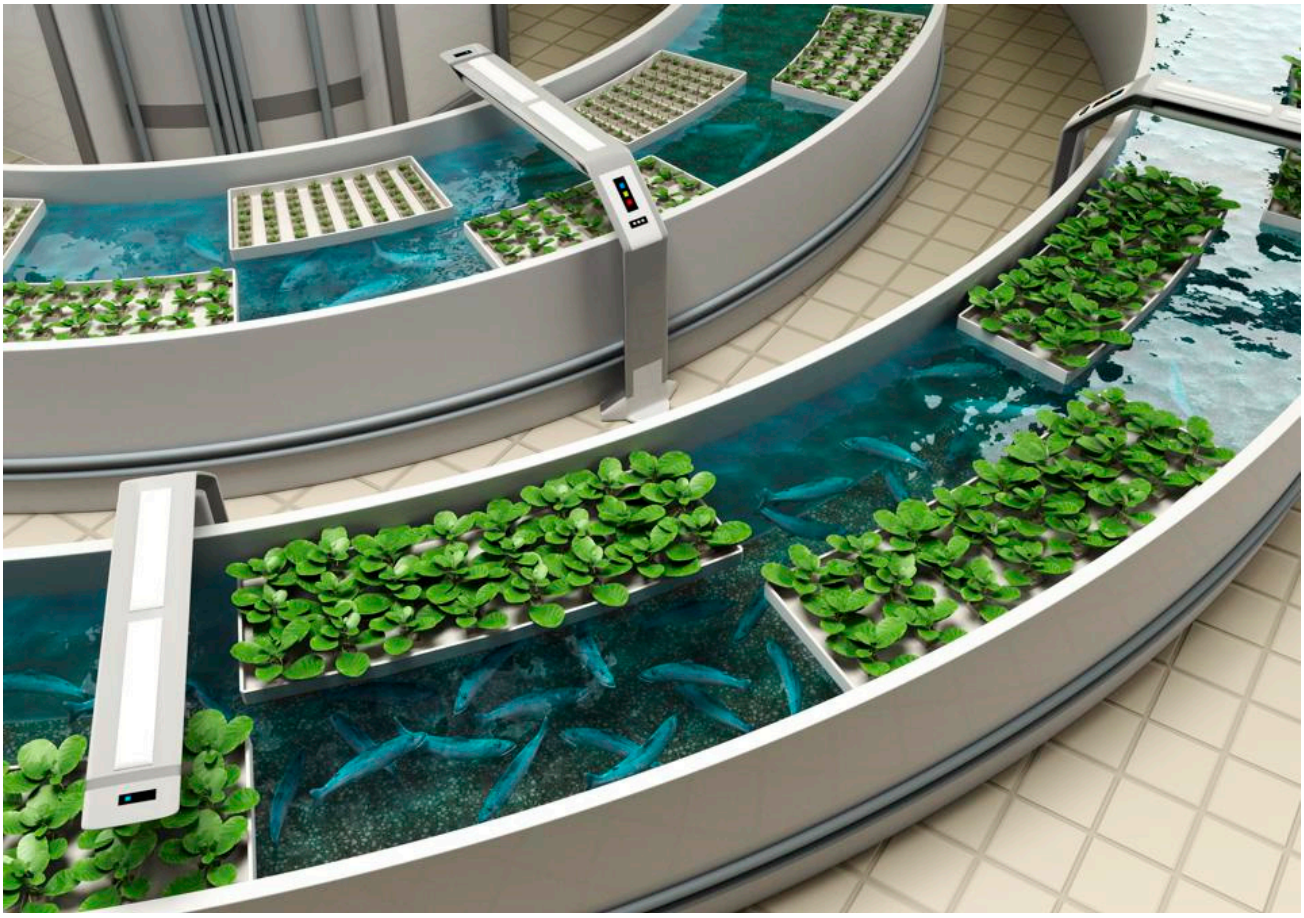

Figure 1. Aquaponics systems with fish tanks water: plants sit closely together in floating foam with no soil using fish excrement as a natural fertilizer (bacteria decompose the fish waste into a form of nitrogen for the plants' growth) [4].

2. Aquaponics/Aquaculture Lifecycle Sustainability

Apart from the types and nature of aquaponics/aquaculture projects, it has centralized aims to meet its goals within its lifecycle. Aquaponics and aquaculture systems follow an elucidative pathway of conceptualization, initiation, planning, implementation, monitoring, and closure to complete the project, either successfully or unsuccessfully. All endeavors along this journey refer to the project lifecycle.

First and foremost, to boost the chance of central control and management of a blended technical-expertise-oriented project such aquaculture and aquaponics, well-defined factors and their proper analysis and selections for a successful project are known to be urgently needed. Concurring with this point, the importance of management and implementation hierarchy becomes manifest. In an aquaponics system, distinguishing and harmonizing types of lifecycles are the most important requirements. Project management lessons and practices classify a technical project lifecycle into main three categories such as:

1. Predictive or fully plan-driven;
2. Iterative—incremental or process-driven;
3. Adaptive—agile or change-driven.

It is generally agreed that the types of lifecycles are differentiated in terms of milestones or sequential implementation of phases (overlapping, depending, parallel, etc.), scope definition levels and interpretations of scope (project level, phase level, milestone level, iteration level, etc.), types of projects and complexity, and level of stakeholder engagements [6]. Thus, the first step toward viable aquaponics project modeling and design starts with selecting a suitable lifecycle analysis. To explore this proposition, types of project lifecycle are retrieved from the PMBOK [7] in Table 1. As per the PMI (Project Management

Institute) report, the adaptive or agile life cycles are primarily applied in the majority of Information Technology (IT) projects.

Table 1. Summary of distinguishing factors for types of project lifecycle [8,9].

	Predictive	**Iterative**	**Adaptive**
Conceptual Characteristics	**Plan-Driven**	**Process-Driven**	**Change-Driven**
Phases implementation	Sequential, overlapping	Sequential, overlapping	Sequential, overlapping, parallel
Scope definition	At the beginning of project	At the beginning of each phase	At the beginning of phase or iteration
Scope description	Covers all project phases	Only for each phase	Only for each phase or iteration
Detailed Planning	At the beginning of project OR rolling wave	Only for each phase	Only for each phase or iteration
Application purpose	Well-defined projects or products	Large and complex projects	Product is not well understood, rapidly changing environments
Stakeholders' involvement	Beginning, when scope changes, and project end	Periodic	Continuous

Maintaining the sustainability of aquaponics system resources is the main part of the system lifecycle, including technical, operational, marketing, promotion, and distributions, and operation team are the leading players to be empowered with competitive knowledge and skills. In principle, a technical project team demonstrates essential skills such as communication skills (listening, understanding, persuading, etc.), organizational skills (planning, prioritizing, analyzing, goal setting, decision-making, etc.), teamwork skills (adaptability, empathy, motivation, etc.), leadership skills (energetic, vision, delegation, positiveness, etc.), coping skills (flexibility, creativity, patience, persistence, etc.), and technical and technological skills (knowledge, awareness, experience, interest, etc.) [10]. The proposed framework in this study is shown in Figure 2.

Performances optimization includes operation and maintenance (and their costs) that need timely observation in terms of monitoring, evaluation, enhancement, control, automation, quality and quantity optimization, etc. Furthermore, there is a link between the implementation phase and efficiency measures achieved by research and development programs to identify options and alternatives, optimize the process, and optimize resource allocation. Therefore, integration management is defined under the project scope, size, and demand. The proposed framework layers distinguish processes and avoid overlap and complication of the process to ensure a systematic and viable roadmap aligned with efficiency measures and sustainability requirements.

The proposed framework describes different layers, focusing on interrelated operations based on given priorities to ensure successful aquaponics system implementation. Therefore, the first part is the core part, including six concepts in an emerging objective supported by management and operation tools and techniques. From a wider perspective, all mention processes follow systematic relations that reduce operation overlaps, optimize resources, and controls the six constraints.

2.1. Concept Design

Aquaponics system design is a multi-step endeavor through a multipass (single and overlap) process that follows conceptualization, feasibility study, preliminary design, descriptive design, modeling, and prototyping phases (Figure 3). However, the design and planning of aquaponics systems can be different with respect to their scope and objectives. In searching for an optimum design solution, these factors are often important: employ assumptions, evaluating analogies, defining critical parameters and their impact, playing with functions and alternatives, altering sequences of steps and process, reversing problem or changing the assessment method and tools, employing basic disciplinary principles, and so on [10].

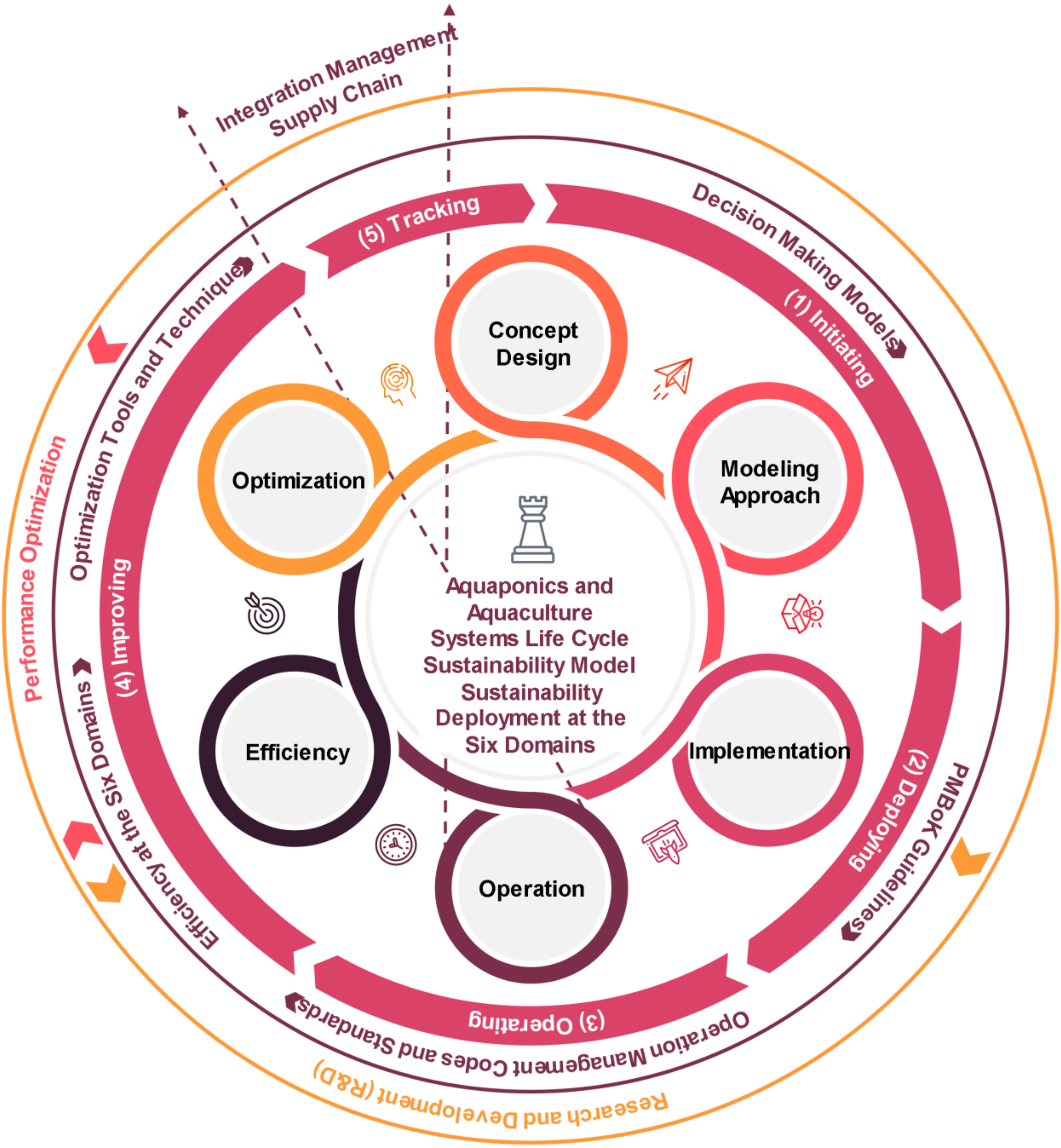

Figure 2. A forefront framework for sustainable aquaponics and aquaculture modeling, design, operation, and optimization.

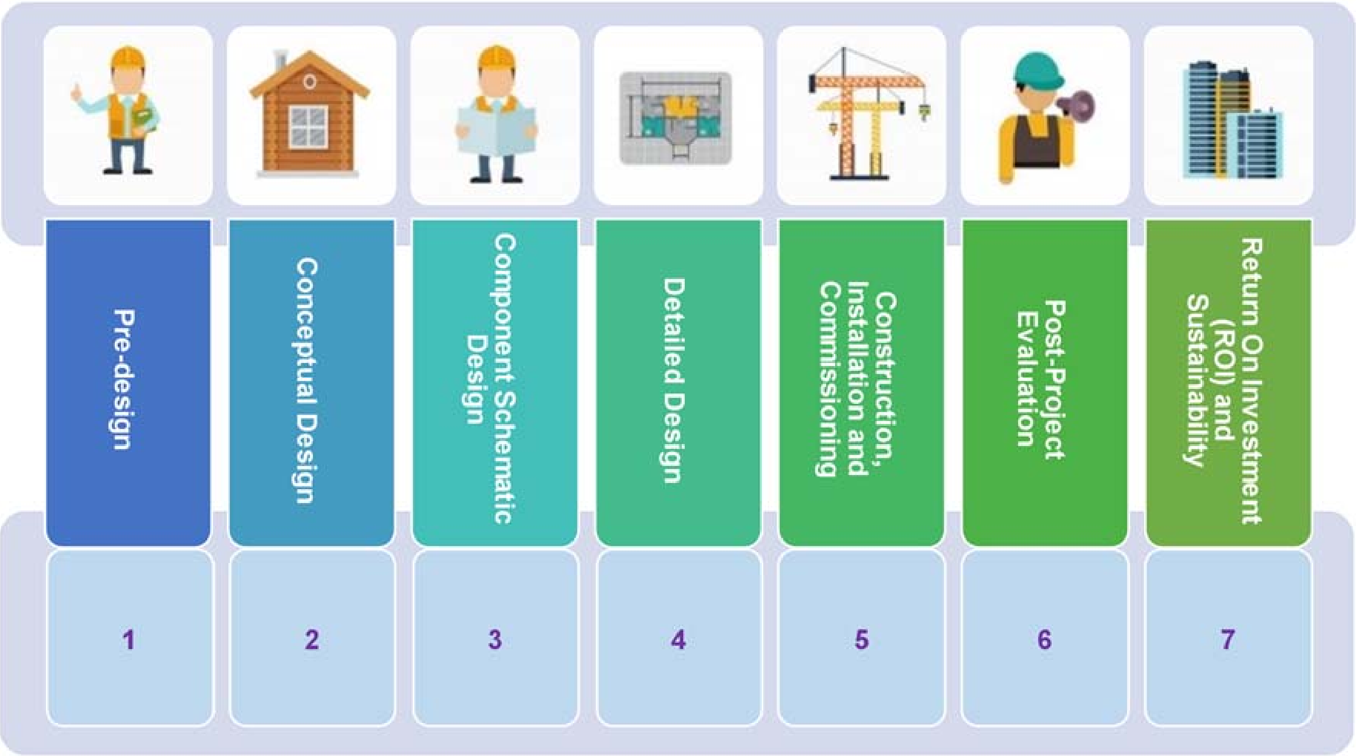

Figure 3. A technical projects design process [11].

2.2. Modeling Approaches

Optimum design and operation of aquaponics systems require masterly analysis of complex interlinked factors to parameterize involving multiple variables of nutrients and organic materials (artificial feeding) that result in an increase in nutrient input, cause decomposition and biochemical oxygen demand (BOD), and limit the carrying capacity of the aquatic system [3]. Various types of decision-making modeling approaches can be applied that are aligned with the aquaponics systems project scope and objectives. The most used types are shown along with their process flow in Figure 4. According to [12], the decision-making process comprises these steps:

- Confirming the scenario score
- Ensuring state statements and goals
- Defining the indicators
- Evaluating indicators interconnection and impact
- Considering the hypothesis impact
- Weighing the indicators
- Considering the overall consequences of outcome and
- Alternatives
- Evaluating the decision, and finally
- Taking proper action

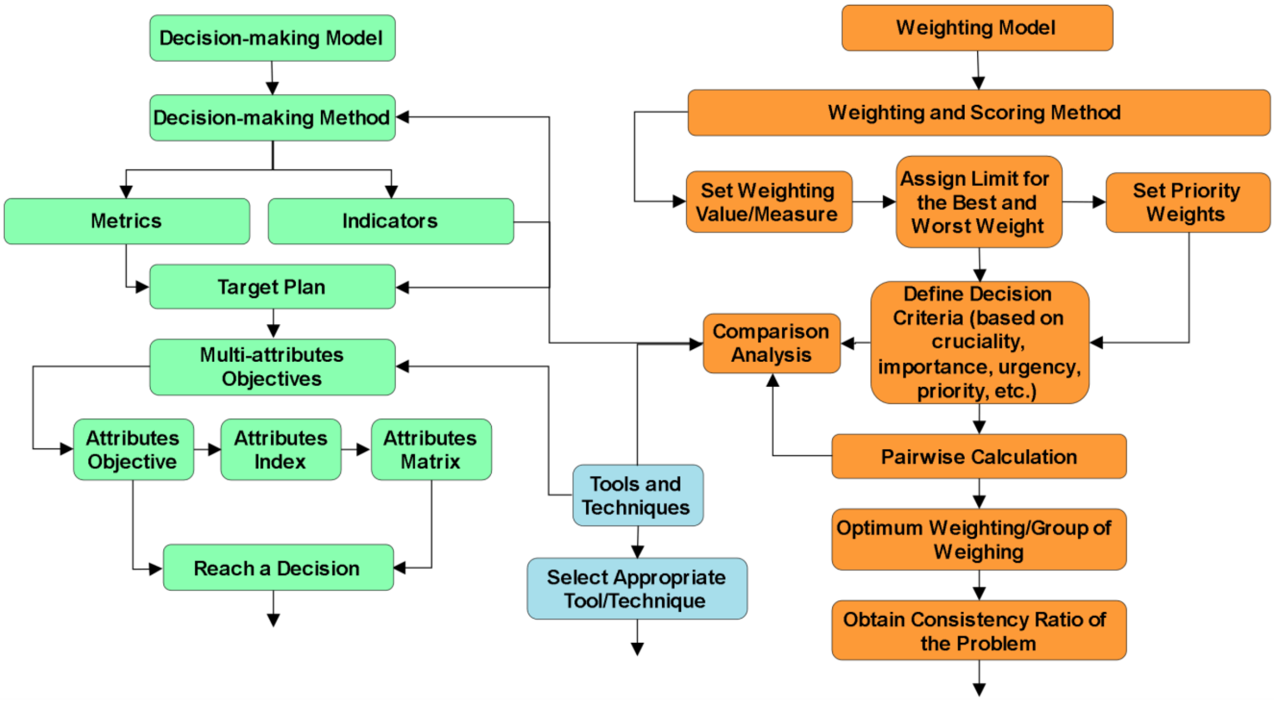

Figure 4. Typical decision-making models and their process flow.

3. Efficiency Measures and Sustainability Pillars

Global consumption of food and non-food aquaculture (46%) and fish products (52%) sales value is estimated at 401 billion USD with an average annual consumption of 20.5 kg per capita per year [1]. This large production and sales figure indicates prominent demand for deployment of aquaponics and aquaculture systems with a clear foresight of increasing demand in the future. With 35% global production, China remained the leading producer in 2018 (Figure 5).

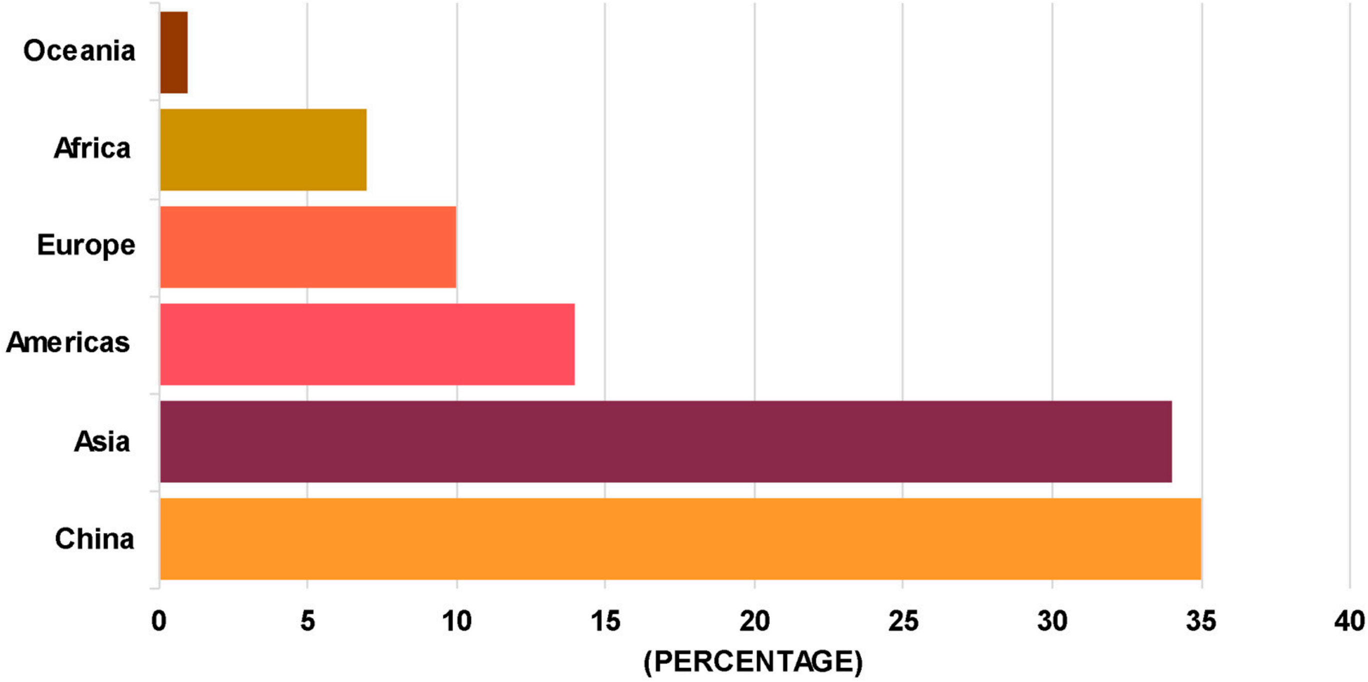

Figure 5. World aquaculture production in 2018 (%) [1].

- Low startup cost;
- Low operation cost including minimum supervision;
- Low management and maintenance cost.

From a broader perspective, capital investment and the treatment systems are costly due to high human resources demand with different skills.

A strategic approach presents and looks to near to long terms as they relate to methodologies, actions, and overall endeavors that target a specific goal [13]. For example, competitive-prosperous modeling and design of aquaponics/aquaculture systems require proper selection and application of tools to develop an energy-efficient power supply and the alignment of indispensable tools and techniques aligned with sustainability requirements. Such an exhaustive framework is proposed in Figure 6.

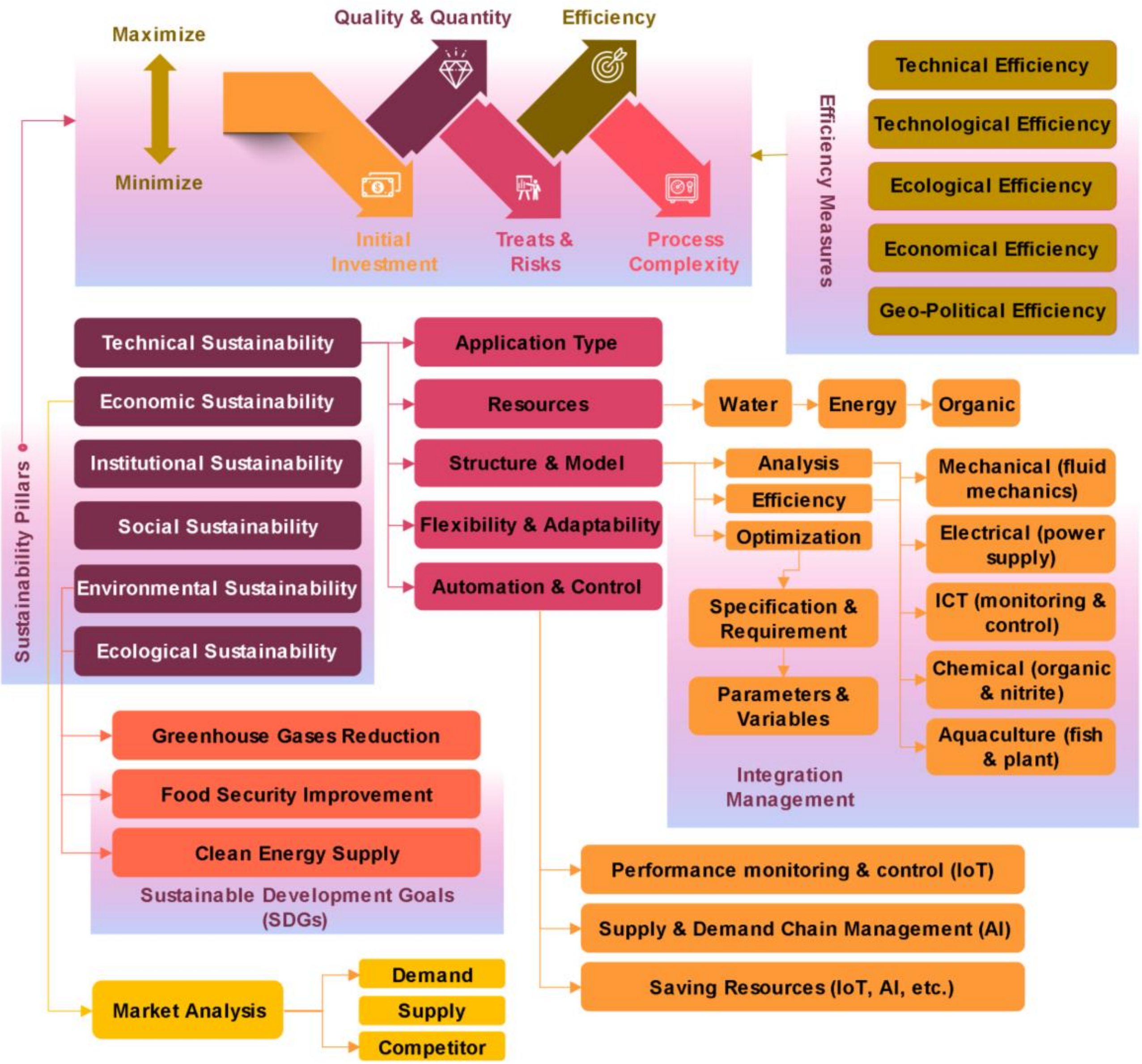

Figure 6. An exhaustive framework for aquaponics/aquaculture systems modeling and design based on efficiency measures and sustainability pillars.

Aquaponics-generated waste is counted as an issue for environmental and ecosystem sustainability. Therefore, to overcome this challenge, the literature has used various approaches such as Triple-R, which stands for Reduce, Reuse, and Recycle, are solutions.

Optimum selection of filtration technologies are aligned with the technical and economic sustainability requirements with low cost of maintenance and long life span. Among these filtration technologies are floating medium filter, sand filter, activated carbon filter, trickling filter, etc., for solid substances, nitrogen, and phosphorus removal. In addition, these filters are used in different structures for specific requirements such as raft water filter, radial flow filter, drum filter, and hybrid filters.

As per the analysis, commercial aquaponics in large-scale filtration mechanisms can be expanded, particularly to address mechanical, biological, and chemical filtration within specific considerations.

Comparison analysis of filters' performance has been done with an average time with specific types of fish by measuring water quality-based effluent criteria in liter per hour. For this process, these parameters can be evaluated using an environmental-quality objective (EQO)-based approach, technology-based approach, or a combination of these approaches for different types of filters performances comparison fit the required parameters (Table 2) [14–16].

Table 2. Aquaponics and aquaculture parameters for aqua products production.

Parameter	Unit
Dissolved oxygen (DO)	mg/L
Ammonia (NH_3)	
Nitrite (NO_2^-)	
Nitrate (NO_3^-)	
Phosphate (PO_4^{3-})	
Ferric chloride ($FeCl_3$) (for flocculation)	
Water Hardness	
Turbidity (NTU)	
Conductivity	(µS/cm)
pH	
Water Temperature	°C/F

These parameters' values depend on types, performances, and specific requirements of fish raising and crop growth of aquaponics systems. Since aquaculture systems are flexible farms with controlled environments, optimum operation can achieve multiple cropping compared to soil-based traditional farms. The main limitation is growing specific aquatic crops and plants.

Density, type, culture, intensiveness, and many other factors should be considered for an appropriate and environmentally fit aquaculture production for production efficiency evaluation within ecological footprint methodology and implication of horizontal integration. The authors of [17] report estimates of standing stock, annual production, and waste generation rates for the tilapia culture within estimated levels for environmental services under semi-intensive tilapia culture as standing stock (0.25 kg m^{-2}); annual production (0.47 kg m^{-2} $year^{-1}$); oxygen (consumption 1020 g m^{-2} $year^{-1}$, and production 2180 g m^{-2} $year^{-1}$); nitrogen output and assimilation (−); and phosphorus (output: 18.3 g m^{-2} $year^{-1}$, and assimilation 21.9 g m^{-2} $year^{-1}$).

In addition to customary ecological criteria for aquatic animals and seafood recommendations, some other criteria have been recently added, such as unit of certification, stock status, non-target species, ecosystem/habitats, forage fisheries, pollution of water, loss of fishing gear, subsidies, use of energy, and CO_2 emissions [18].

Environmental pollution predominantly applies to greenhouse gases emissions such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) [19]. However, energy production and consumption contribute about 37% of global warming [20].

Advancement of aquaponics systems with high efficiency of production are associated with the risk of ecosystem unbalance. Especially when using natural resources as production inputs, such as farm land, water and energy supply, feeds, chemical and organic wastes that can contribute environmental distress. Additionally, aquaponics expansion in terms of industrial trade with high production inputs results in a similar range of production outputs that raise ecosystem and environmental concerns, comprising airborne and waterborne emissions from the farms [3]. However, there is uncertainty in accurate qualitative impact assessment of environmental distress to human health and ecosystem due to unresponsiveness of emission to changes in waste composition [2].

In [21], scientific and technological challenges are addressed in three main categories for today's aquaponics system: nutrients, water, and energy. Nutrient-rich water reclamation and recycling cycle from fish to crops grown for near-zero nutrient loss in the process is important, as is reusing water technology for a system within acceptable pH levels. Clean and green power supply remains the core of the entire operation to ensure moderate water temperature, water filtration, recirculation, etc. In addition to nutrient, water, and energy resource challenges, land use, waste management, and complying with the recent constrained environmental regulations are important points.

As discussed in previous sections, sustainability pillars deployment ensures efficient aquaponics operation if all factors and measurements are put together within a single approach for long-term sustainability. Institutional sustainability plays a vital role in commencing environmental and ecological sustainability requirements, obligations, and procedures ahead of project initiation. This process can be referred to as permission or licensing for aquaculture establishment issues by the local government. The main purpose behind this process is to confirm organic, inorganic, and operational wastes management and ensure the system's proper operation and management within standards and codes [22].

Nutrient-rich water and upwelling can affect marine life by changing water temperature, dissolving CO_2, diversity in pH measures, and the overall ecosystem. Therefore, the impact of nutrient-rich water discharge on coastal and ocean waters is an important consideration [23]. Environmental sustainability, which depends on various factors, is crucial for ecosystem sustainability for environmental regulatory bodies. In the context of nutrient-rich water and other anthropogenic activities, including modern agriculture and fish-rearing industries, understanding the concentration of nutrients forms (ammonium, nitrite, nitrate, and organic nutrient) and its efficient transformation for efficient use is urgently needed.

In the case study in [15], recommended cultivation amount as per the Environmental Protection Agency (EPA) for marine prawn aquaculture farms should meet stringent load based effluent discharge requirement per hectare as follows:

- 12 kg/ha per day of total suspended solids;
- 1 kg/ha per day of total nitrogen;
- 0.15 kg/ha per day of total phosphorus.

Aquaponics systems are widely used for above-mentioned purpose in different countries [24–28], with the anticipated outcomes. Competent human resourcing and team building for competitive decision-making pay off. Aquaponics operation and routine teams require diverse abilities and technical knowledge, creativity, planning, and management to ensure interdependency, cohesiveness, roles and norms, and communication throughout the system [10].

Aquaponics reports are often based on specific measures in terms of the fiscal year for evaluation of environmental and monetary benefits as follows:

- Net production in—in tons;
- The net value of producing products—in any currency units;
- Increase/decrease rate (compared to a benchmark: year, months, or other indicators)—in terms of quantity/monetary;
- Target to reach (based on timeline or monetary span)—in terms of quantity/money;
- Contribution to environmental sustainability (monetary and nonmonetary)—amount of greenhouse gases emitted, amount of waste generated and disposed of, amount

of water deranged and reused, rate of mechanical and electrical energy saved and recovered, cost of environmental conservation, area of land optimized, contribution to research and development of codes and standards, socio-economic impact of environmental conservation activities, etc. [29]. Often, analytical assessment tools such as ecological footprint (EF) [17,30,31] and life cycle assessment (LCA) [32,33] techniques are used for environmental impact assessment.

4. Conclusions

The contribution of aquaponics and aquaculture systems to world food supply and nutritional security has been reported intensely for the last two decades. In addition to optimally producing aqua products, integration of aquaponics and aquaculture into the global food system in terms of quantification, valuation, and market development in the way of sustainable development persists, with a dramatic impact on world nutrition security and marine ingredients, and reliance on the terrestrial ecosystem has remained rare. This research effort emphasizes that sustainability requirements throughout includes reporting of aquaponics and aquaculture, idealizing and conceptualizing, modeling, designing, management, and aligning these requirements within technical, technological, economic, ecological, environmental, and institutional sustainability pillars. Furthermore, balancing resources, processes, tools, and techniques can play a vital role in aquaponics and aquaculture sustainability, as shown in Figure 7.

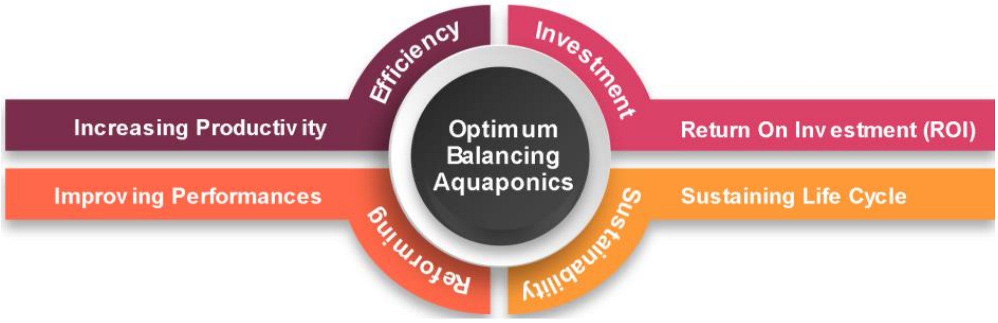

Figure 7. Optimal balancing of aquaponics/aquaculture systems key factors within socio-economic consideration for maintaining long sustainability.

The overall objectives of the paper are to enable readers to correctly model and design their aquaponics project by employing the emerging interdisciplinary practices offered by decent theoretical and industrial recommendations.

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