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RESEARCH AND ANALYSIS

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Evaluation of environmental and economic implications of a cold-weather aquaponic food production system using life cycle assessment and economic analysis

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Abstract

Aquaponics, in which fish and plants are grown in a symbiotic closed-loop industrial metabolism, are promising test beds to implement industrial ecology in food production at a commercial scale. These systems have the potential to enhance the environmental and economic performance of aquaculture systems by reducing the overall burden on natural ecosystems (i.e., reducing resource and emission-based impacts per unit of food produced). To holistically evaluate the environmental and economic implications of aquaponics, specifically in a cold-weather climate, Life Cycle Assessment (LCA) and Economic Analysis (EA) were performed on a Midwestern United States aquaponic system, using data from 3 years of annual operation cycles with varying fish species production; tilapia, conventional walleye, and hybrid walleye. For the LCA, environmental impacts were quantified using 10 midpoint indicators. Assessments indicated that 1-kg production of live-weight tilapia, conventional walleye, and hybrid walleye resulted in 20.2-13.8-11.7 kg CO_2-eq, 23.0-7.8-3.9 g N-eq, and 0.2-0.3-0.4 kg SO_2-eq, consecutively, using the investigated system. The most sensitive parameters for environmental impacts were heat, aquafeed, electricity, and infrastructure (in all scenarios). For EA, benefit to cost ratios (BCRs) and three other widely used indices were analyzed for production cycles. The BCRs were 0.47, 1.16, and 1.75 for tilapia, conventional walleye, and hybrid walleye, respectively (using a 10% discount rate and a 20-year horizon), highlighting the necessity of optimizing both cash inflows (e.g., energy costs) and outflows (plant and fish revenues) to achieve practical enhancement of return on investments. The major cost contributors were infrastructure, labor, and heat (contributing to >89% of total costs for all cycles). Suggested steps for in-effect improvement of the investigated aquaponic system's environmental and economic favorability include heat and infrastructure optimization by (a) applying effective heating strategies (e.g., advanced insulation techniques), and (b) expanding the system's operational lifespan (e.g., prevention of waste accumulation).

KEYWORDS
aquaponics, economic analysis, environmental impacts, industrial ecology, life cycle assessment (LCA), sustainable aquaculture

1 INTRODUCTION

Symbiotic integration of nutrient cycles is prospectively a sustainable food production strategy that mitigates waste and damages to ecosystems by implementing a closed-loop circular approach (Delaide et al., 2017; Tibbs, 1992). Implementation of aquaponics, which is a combination of aquaculture and hydroponic systems, is one potential solution to reduce adverse environmental impacts of aquaculture (e.g., eutrophication and water consumption) while maintaining the economic gains by adding to production types and quantities through symbiotic fish and plant growth (Boxman et al., 2017; Cohen et al., 2018; Xie & Rosentrater, 2015). As more products are generated and less waste is emitted per cycle of aquaponic production, combining these systems is anticipated to be a more environmentally and economically sustainable food production process compared to separate aquaculture-agriculture processes (Adler et al., 2000; Goddek et al., 2015; Xie & Rosentrater, 2015).

With respect to environmental sustainability, many studies evaluated the environmental impacts of aquaponics (Bohnes et al., 2018; Cohen et al., 2018; Kalvakaalva, 2020; Maucieri et al., 2018; Somerville et al., 2014; Song et al., 2019; Wu et al., 2019). Cohen et al. (2018) found that combined aquaponic fish-vegetable production would result in significant reduction of impacts in eutrophication, water intake (water use), and geographic footprint (land use) environmental impact categories, compared to large-scale traditional non-integrated production (Cohen et al., 2018). Ghamkhar et al. (2020) compared the environmental impacts for carnivorous cold-water fish production in an aquaponic system to conventional farm impact values and highlighted a notable reduction of impacts in acidification and eutrophication by aquaponic production. Despite the value of the current knowledge on the environmental impacts of aquaponics, there are three main gaps with respect to the environmental analysis of aquaponics: (a) The investigated impacts usually only cover a limited subset of the relevant environmental impact categories (Bohnes & Laurent, 2019; Wu et al., 2019); (b) the investigated systems are predominantly located in warm weather locations, in which heating and lighting requirements are relatively lower; and may not be representative to cold weather locations, in which heat requirements are relatively high (Wu et al., 2019); and (c) applied alternatives to mitigate the environmental impacts of aquaponics are not fully explored within the studies (Ghamkhar et al., 2020).

With respect to the economic sustainability of aquaponics, the body of literature is relatively limited with few successful commercial examples (Bich et al., 2020; Greenfeld et al., 2019; Love et al., 2014; Quagrainie et al., 2018). Chaves et al. (1999) compared the economic profitability of coupled catfish and tomato production in an aquaponic system with catfish production in a similar recirculating aquaculture system and found that there is little difference in financial results at the margins budgeted (rate of return = 27.32%). Tokunaga et al. (2015) investigated the economic feasibility of three aquaponic farms in Hawaii and revealed a slight economic benefit of a small-scale commercial aquaponic operation (rate of return = 7.36%). High variation of results among studies on aquaponic economic analysis is potentially due to variations in material and energy flows among different systems. Therefore, it highlights the importance of performing a case-specific economic evaluation of aquaponic food production in a cold-weather location.

In order to provide a holistic environmental-economic evaluation of aquaponic food production, life cycle assessment (LCA) and economic analysis (EA) were applied as quantification tools within the concept of industrial ecology (Bare et al., 2012; Garner & Keoleian, 1995; Konstantinidis et al., 2020). A holistic set of contributing parameters (inventory data), relevant environmental impact categories, and economic indicators were incorporated to provide a systematic perspective regarding aquaponic sustainability. Furthermore, major contributors were identified in order to determine the next steps to improve the environmental and economic sustainability of aquaponic food production (Song et al., 2019).

This work used LCA and EA to provide a comparative environmental and economic evaluation of a research-scale, cold-weather aquaponic system (US-Midwest), which cultivated varying aquatic species in different years along with varying vegetables. A holistic set of environmental impact categories (10 impact categories) and economic indices (4 indicators) were employed to determine major contributing parameters and potential strategies to enhance environmental and economic favorability of the aquaponic food production system.

The paper is organized as follows: Section 2 consists of system description (Section 2.1), goal and scope definition (Section 2.2), and life cycle inventory (Section 2.3). Afterwards, results for this analysis were organized in Section 3. Section 3.1 covers the environmental impact assessment and sensitivity analysis of the investigated system under different treatments. Section 3.2 explains the economic analysis results and the contribution of different factors in the economic performance of the aquaponic system. Further discussions regarding the results of this study as well as potential future research based on the outcomes were made in Section 4. Finally, conclusions are presented in Section 5.

2 METHODS

2.1 System description

A combination of six identical, entry-level aquaponic systems, each consisting of two fish tanks, two clarifiers, two mineralization tanks, one communal bioreactor/degassing tank, four rafts, one sump tank, one heater, one water pump, one air pump, covering nets, 144 rockwool cubes, and four light bulbs and fixtures were used in the investigation. A simplified overview of the infrastructure parameters for the aquaponic system is illustrated in Figure 1. The system's operation was investigated for three different annual production cycles (2015, 2016, and 2017) to produce

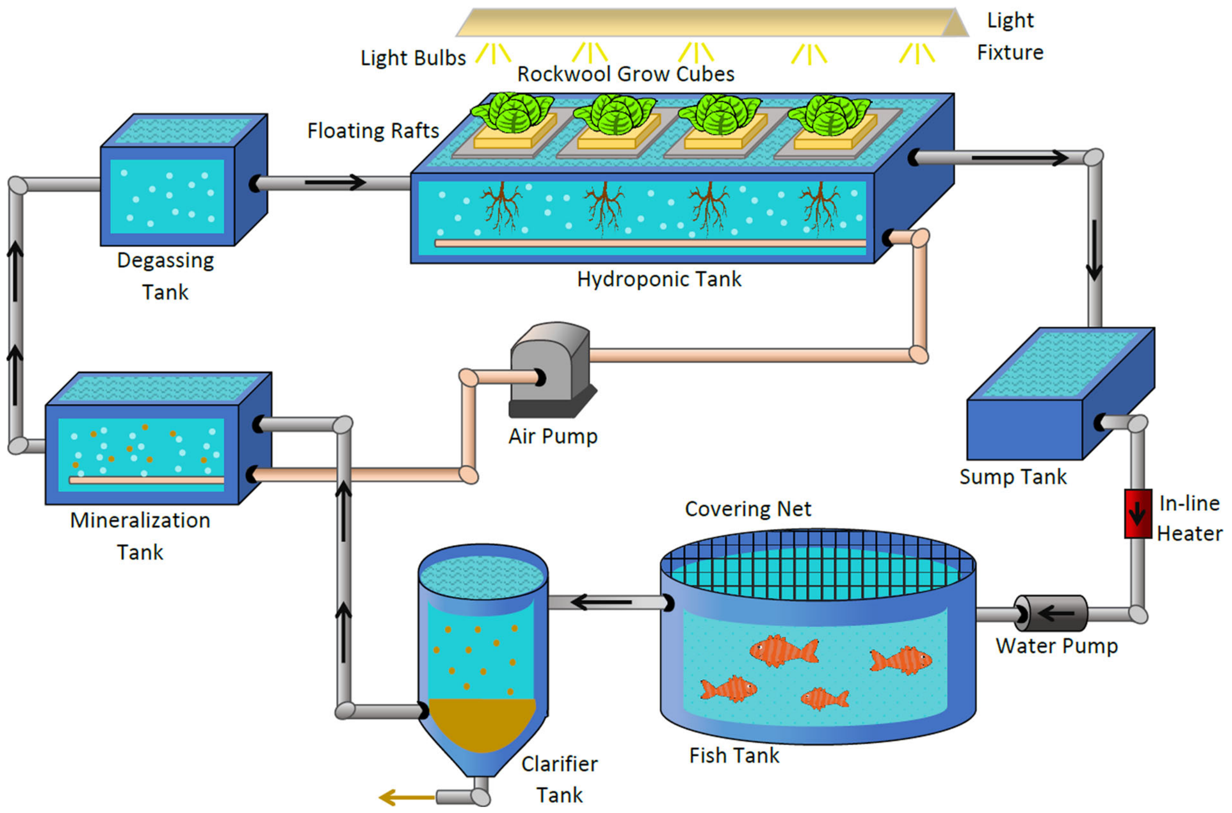

FIGURE 1 Simplified overview of the aquaponic system (quantities of each component is excluded). Arrows within the pipes indicate the water flow direction

vegetables (butterhead lettuce (*Lactuca sativa* L.), Romaine lettuce (*Lactuca sativa* L. var. longifolia), pak choi (*Brassica rapa)*, and kale (*Brassica oleracea* var. sabellica)) along with tilapia (*Oreochromis niloticus*), conventional walleye (C-walleye, *Sander vitreus*), and hybrid walleye (H-walleye, *Sander vitreus x Sander canadensis*), respectively. Each analyzed scenario represented one year of production.

In each aquaponic system, fishes were fed with a commercially available dry feed with the protein and nutrients required by each fish type. Consequently, the excreted waste contained dissolved nutrients, such as ammonia (NH_3), as a product of fish metabolism. The nutrient-rich water was directed to the clarifiers to remove most of the solids waste. Using nitrification and mineralization, NH_3 was oxidized into nitrite (NO^{2-}) and then nitrate (NO^{3-}), which was less harmful to aquatic species, and provided the essential macro- and micro-nutrients for the plants. After degassing, the nutrient-containing water was directed to the raft tanks, where the plants consumed the inorganic ions through nutrient uptake. Finally, water was directed to the sump tank, which acted as a controller for water level fluctuations in raft and fish tanks.

2.2 | Goal and scope definition

The main goal of this study was to determine the environmental and economic implications of a cold-weather aquaponic food production system, located in the Midwestern US. The investigated system included a comprehensive set of processes and factors that posed associated environmental impacts and economic considerations.

2.2.1 | System boundary

The final product of the system was food for human consumption (in terms of fish and plants) at the aquaponic "gate"; this study was a cradle-to-gate assessment. Post-farm processes (e.g., packaging, transportation, distribution, use, end of use) were excluded from the scope of this assessment due to the lack of reliable data and potential variation in post-farm scenarios (Ghamkhar et al., 2020). To incorporate the multi-functionality of the aquaponic system, mass allocation was selected to partition the environmental impacts to both co-products (fish and plants)

(Hindelang et al., 2014). The functional unit for the midpoint impact assessment was considered as the impact per kilogram of live-weight fish (product) produced annually in the research-scale aquaponic system, due to the intended function of the system as fish production.

2.2.2 | Evaluation criteria: Environmental

LCA is a standardized method conceived to assess the environmental impacts associated with a product or process (Berardy et al., 2020). According to the International Standard Organization guidelines (ISO14040-14044), LCA is comprised of four steps: goal and scope definition, inventory, impact analysis and results interpretation (ISO-Norm, 2006; Wu et al., 2020). In the goal and scope definition, the motivation for performing LCA, product system boundary, functional unit, and data parameters is defined (Hicks et al., 2020). In the inventory stage, resources consumed and emissions to the environment at all stages of a process's lifespan, from the raw material extraction to the disposal of waste, are quantified (Guinée, 2002; ISO, 1997). In the impact analysis step, identification and evaluation of key issues are made. In the end, recommendations and conclusions are made in an interpretation step (Lee & Inaba, 2004).

SimaPro 8.2.0 was used for the LCA as the modeling platform, using databases from Agri-footprint (Durlinger et al., 2014), Ecoinvent-3.4 (EcoInvent, 2014), European reference Life Cycle Database (ELCD) (Goedkoop et al., 2008), and the United States Life Cycle Inventory (USLCI) (Norris, 2004) databases.

To provide a holistic impact assessment, multiple impact categories, which are characterized by US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1, were investigated. The included TRACI 2.1 midpoint environmental impact categories (abbreviation, unit) were ozone depletion (OD, kg CFC-11-eq), global warming (GW, kg CO_2-eq) (time horizon: 100 years), photochemical smog (PS, kg O_3-eq), acidification (AC, kg SO_2-eq), eutrophication (EU, kg N-eq), human health carcinogenics (HHC, CTUh), human health noncarcinogenics (HHNC, CTUh), respiratory effects (RE, kg $PM_{2.5}$-eq), ecotoxicity (EC, CTUe), and fossil fuel depletion (FF, MJ surplus). For each environmental impact category, the total quantity of chemical emission or resource utilized was multiplied by its estimated potency. This methodology (TRACI 2.1) is reported to be based on the best available models and data in the United States, which allows a desired level of comprehensiveness and accountability (Bare et al., 2012). For all investigated impact categories, Monte Carlo simulations in SimaPro 8.2.0, for 1000 runs to the 95th confidence interval was performed in order to visualize and estimate the total variations in output parameters (Tables S10–S12 in the Supporting Information) (von Brömssen & Röös, 2020). These assessment methods followed the problem-oriented midpoint approach, which means that results were expressed in terms of their potential environmental impacts rather than actual damage levels (Pelletier & Tyedmers, 2010).

2.2.3 | Evaluation criteria: Economic

Year-round operation of the investigated aquaponic system (located at University of Wisconsin-Stevens Point Aquaponic Innovation Center) was investigated to account for different aquatic species produced at different years. Tilapia, C-walleye, and H-walleye were produced along with different vegetables during 2015, 2016, and 2017, respectively. Tabulated and categorized set of infrastructure costs, operating costs, and revenues for the investigated aquaponic system is provided in Tables S4–S8 in the Supporting Information.

Compiling the financial parameters associated with the aquaponic system operation under different conditions (e.g., produced species, heating requirements etc.) provided the opportunity to use financial indices to perform a comprehensive economic analysis. The financial tool indices used in this study were Net Present Value (NPV, aka Net Present Worth) (Nagalingam, 1999), Internal Rate of Return (IRR) (M. T. Chen, 1998), Payback Period (PBP) (Wildern, 1997), and Benefit to Cost Ratio (BCR) (Shively & Galopin, 2013). An annual interest (discount) rate of 10% (Rupasinghe & Kennedy, 2010), and a 20-year operation horizon (Ghamkhar, Hartleb et al., 2020) were considered for the calculations. Detailed explanation on the methodology and inventory regarding economic indices is provided in Tables S4–S8 and Section S8 (8.1–8.4), all in the Supporting Information.

2.2.4 | Evaluation criteria: Sensitivity and contribution analysis

To quantitatively identify the input and output parameters to which the results of the investigated system were sensitive (with corresponding changes in the impact results), a complementary sensitivity analysis was performed for all environmental indicators and production cycles. For each parameter listed in the inventory, the value was modified by $\pm$20%. The updated impacts of the existing system were re-calculated to determine how the change in input affected the impacts for each indicator or impact category. The relative change of the output terms was compared with the relative change of the input terms to calculate the sensitivity factor (SF). For any given parameter, if the calculated sensitivity factor (SF) was less than 0.1 for all impact categories, the sensitivity of final output to that parameter was considered negligible (non-sensitive parameter). For complementary economic analysis, contribution analysis was selected to be performed rather than sensitivity due to two main reasons: (1) Illustration of the economic contribution results provided a simplified glance with similar conclusions; (2) As opposed to environmental impact categories, which

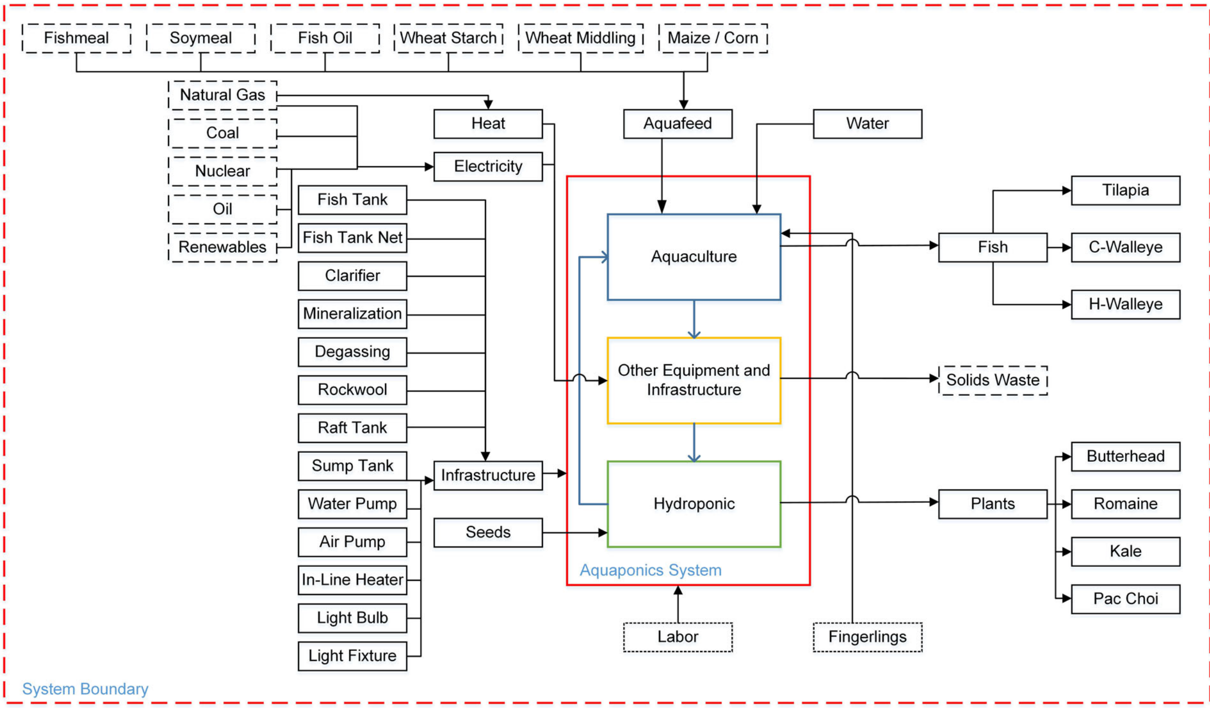

FIGURE 2 Materials and energy flow diagram and system boundaries of the aquaponics system. Dashed boxes indicate parameters that are expanded for LCA. Dotted boxes indicate parameters that are expanded for EA. Blue arrows indicate the water flow within the aquaponics system, while black arrows indicate materials and energy inputs/outputs within the system boundary. Underlying data for Figure 2 are available in Tables S1–S3 of the Supporting Information

TABLE 1 Aquaponics system operation key parameters with respect to different production cycles

Parameter	2015: Tilapia production	2016: C-Walleye production	2017: H-Walleye production
Feed conversion ratio (FCR)[a]	2.47	5.41	3.40
Electricity (kWh)	5370	6657	8614
Heat (m^3)	2382	3050	3502
Fish production (kg)	555	350	284
Vegetables production (kg)	91	837	1165

[a]Quantified as kilogram of feed/kg of produced fish.

were representing different indicators, economic indices explained and compared the favorability of the system cycles in one aspect, which was fiscal performance. To perform contribution analysis, all parameters were fragmented and expressed in terms of net present costs (NPCs). The contribution of each parameter to the overall systems' net present cost (NPC = −NPV) was considered as the parameter's contribution to the overall economic performance.

2.3 | Life cycle inventory

To conduct a holistic assessment, a comprehensive set of material and energy inputs and outputs was compiled from all three production cycles (2015, 2016, and 2017). The incorporated parameters were inputs (electricity, heat, aquafeed, seeds, infrastructure, fingerlings, water, and labor) and outputs (fish, plants, and solids waste). Figure 2 demonstrates the flow diagram of the aquaponic system investigated in this study.

A simplified overview of the system operation key parameters with respect to different production years is provided in Table 1. Detailing inventory data is provided in Tables S1–S3 of the Supporting Information.

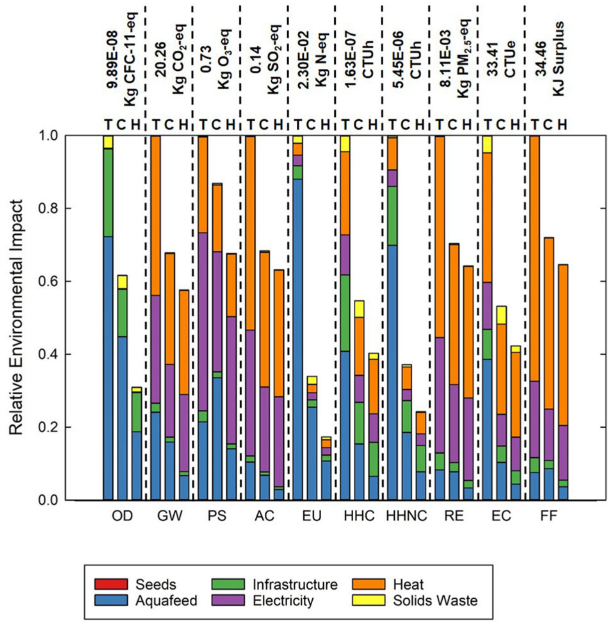

FIGURE 3 Relative Environmental Impacts of the aquaponics system year-round operation per kg of live-weight of fish produced: results for 2015 (tilapia production, T), 2016 (C-walleye production, C), and 2017 (H-walleye production, H). Numbers on the upper bar represent the quantified environmental impact value of the top 1 in each category. Underlying data for Figure 3 are available in Tables S10–S12 of the Supporting Information

2.3.1 | Assumptions

The annual water consumption was assumed to be constant among different operation years as a result of: (1) Indoor greenhouse temperature, pressure, and relative humidity were kept unchanged over three production years ($P = 1$ atm, $T = 23°C$). Therefore, the vaporization flux and consequent make-up water requirement was constant. (2) System equipment and infrastructure were not changed over the investigated years. Thus, the initial fill-in water requirement were also constant. In spite of similar pumping and lighting requirements for the system throughout different years, the rearing species have different temperature tolerance ranges, posing varying in-line heating and chilling demands. Accordingly, the utility data for different production years was used to acquire the system's electricity usage. The electricity sources were selected based on the provider's resource fractions (38% natural gas, 37% coal, 4% oil, 21% renewables (2017 Corporate Sustainability Report—Alliant Energy, 2017)). Space heating demand changed for different production cycles, simply because the atmospheric temperature conditions varied across the investigated years, requiring different heating to keep the indoor temperature constant at 23°C. The overall final quantity of vegetables produced was dissimilar across different years due to the availability of nutrients (nitrogen phosphorus etc.) in the circulating flow, the operators' experience in hydroponic cultivation, and the species of fish produced. As the overall amount of generated solid waste was not available for two (out of three) production years, the ratio of solid waste/mass runoff (mass of feed – mass of produced fish) was assumed to be constant over different production cycles (≈0.35) to calculate the estimated solids waste generated.

3 | RESULTS

3.1 | Environmental implications

A quantitative environmental impact assessment of the aquaponic food production process, attributed to the system inputs and outputs according to different operational conditions (tabulated in Tables S1–S3 in the Supporting Information) utilizing mass allocation over a 1-year process, was performed. Results based on production of 1 kg live-weight of fish are illustrated in Figure 3.

With respect to all TRACI impact categories for all production years, more than 90.7% of total environmental impacts were attributed to four parameters: aquafeed, infrastructure, electricity, and heat. These parameters represent the impact hotspots in the aquaponic system analysis (Ghamkhar et al., 2020).

For all impact categories, the quantified environmental impacts were following the order of T (2015, tilapia) > C (2016, C-walleye) > H (2017, H-walleye), despite the elevated energy demands throughout the years (heat + electricity) due to temperature variations. As aquafeed demands

TABLE 2 Comparison of global warming (GW) and eutrophication potentials (EU) resulted from this study and other food production systems (recirculating aquaculture, net pen aquaculture, land-based aquaculture, lake-based aquaculture, beef, and poultry)

System type	Reference	Global warming (kg CO_2-eq/kg live-weight)	Eutrophication (kg N-eq/kg live-weight)[b]	Characterization method[c]
Aquaponic	This study	11.67–20.26	0.0039–0.0230	TRACI 2.1
Aquaculture (recirculating)	Aubin et al. (2006)	6.02–10.64	0.1455–0.1801	GW: IPCC (1996) (Houghton, 1996) EU: Tukker et al. (2002)
Aquaculture (recirculating)	Song et al. (2019)	16.70	0.0057	GW and EU:ReCiPe, v1.13
Aquaculture (net-pen)	Ayer and Tyedmers (2009)	2.07	0.0353	GW and EU: CML 2 (Baseline 2000) (Guinée, 2002)
Aquaculture (land-based)	Smárason et al. (2017)	2.22	0.0547	GW and EU: CML 2 (Baseline 2000) (Guinée, 2002)
Aquaculture (lake-based)	Pelletier and Tyedmers (2010)	2.76	0.1154	GW and EU CML 2 (Baseline 2000) (Guinée, 2002)
Beef	Ogino et al. (2016)	10.6–14.0	0.0711–0.0793	GW: IPCC (2007) (Solomon et al., 2007) EU: MiLCA Database
Poultry[a]	Williams et al. (2006)	4.58	0.1147	GW: IPCC 2001 EU: Source not mentioned.

[a]Quantified impacts for this system are based on the functional unit of carcass dead weight.
[b]Following TRACI 2.1 characterization method, relative ratio of 1:2.38 is used for the harmonization of freshwater (PO_4^{3-}eq) into N-related marine impacts (N-eq) (Morelli et al., 2018).
[c]Life cycle impact characterization methods for global warming and eutrophication.

and waste generation have been increasing from T to C and decreasing from T to H, the reduced environmental impacts were due to the increase in the amount of final product (fish + plants), due to more efficient operation of the system through the years. As the total amount of produced live-weight fish was reduced from T to C and H (since fry walleye weigh ~200 g less than tilapia), the overall increase in final products' mass was attributed to elevated plants production. This was in line with the findings of Love et al. (2015), and highlighted the importance of system operation experience, specifically regarding plant production, to elevate system outputs and consequently elevate systems environmental performance per unit of product (Love et al., 2015; Winther et al., 2020).

Quantified impact results from this study were compared to some other fish and animal production methods (e.g., net pen aquaculture, beef, etc.). A summary of the results for GW and EU (per live-weight product) is tabulated in Table 2. Despite different scopes and characterization methods for different LCA studies, comparison of impacts difference of magnitude helped to have a better understanding of the system's environmental performance compared to other food production systems (Guzmán-Luna et al., 2021).

As shown in Table 2, the resulting EU impacts from the investigated system in this study were lower than other investigated production systems except for recirculating aquacultures (aquaculture: net pen, land-based, lake-based; beef; poultry) by ~1 order of magnitude. This was mainly due to the internal use of micronutrients (N and P) within the aquaponic system instead of emitting them to the environment (Bergman et al., 2020). However, the resulting GW impacts from the investigated system were either slightly higher or at the same level compared to other analyzed food production systems. Based on the relative Global Warming impact assessment results for three investigated production cycles (as well as the sensitivity analysis results, which was further explained in the next section), heat was a major contributor of the GW impacts. The elevated heating demands for the investigated aquaponic were expected due to the location of the system (cold weather climate). However, in a hypothetical scenario that heating requirements were neglected, the GW impacts of the aquaponic system would reduce to 5.7 to 11.4 kg CO_2-eq, which was a slightly lower range compared to the analyzed recirculating aquacultures and beef production. Considering the mitigation of impacts regarding other environmental indicators (e.g., EU) (Ghamkhar, Hartleb et al., 2020), expected economic gains due to multi-functionality of aquaponics (further investigated in the next sections) (Blidariu & Grozea, 2011; Tsakiridis et al., 2020), and the elevation of food systems resiliency via local production (Turnšek et al., 2019), implementation of aquaponics food production is still a potential sustainable approach. However, strategies to reduce the environmental impacts of such setups in cold-weather environments regarding global impact categories (such as GW) need to be analyzed and executed.

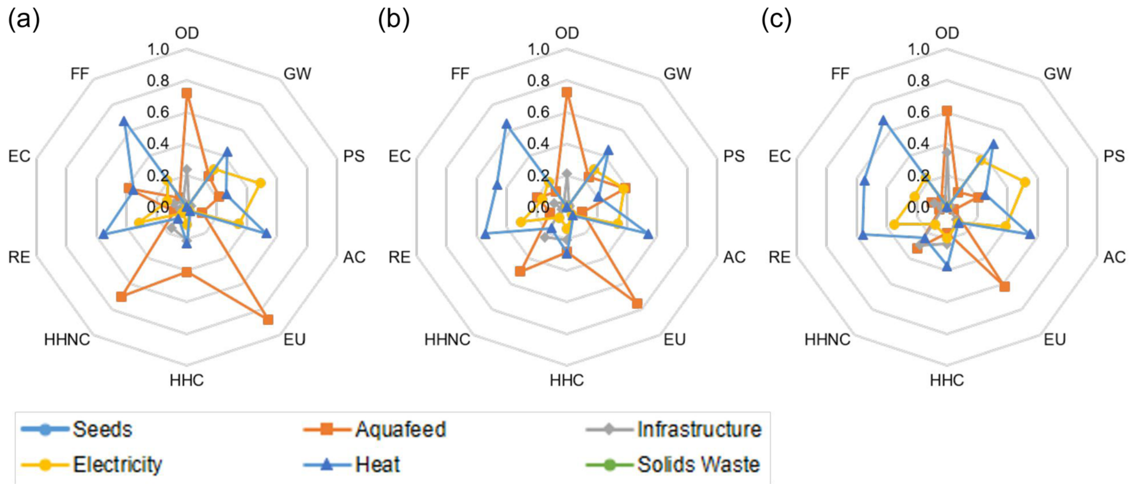

FIGURE 4 Sensitivity Factors (SFs) for the contributing parameters regarding TRACI impact categories for (a) 2015, tilapia production, (b) 2016, C-walleye production, and (c) 2017, H-walleye production. Underlying data for Figure 4 are available in Tables S13–S15 of the Supporting Information

3.1.1 | Sensitivity analysis

To quantitatively evaluate the overall sensitivity of final economic evaluation results with respect to the initial investment parameter (infrastructure cost, operating costs, and total revenues), sensitivity analysis was performed. Sensitivity factors (SFs) were calculated as |Percentage of change in final NPV| / |Percentage of change in the input parameter| and illustrated in Figure 4. Absolute SFs for the investigated production cycles are provided in Tables S13–S15 in the Supporting Information.

For all production cycles, seeds and solids waste posed negligible SFs (<0.1 for all impact categories). Contrarily, aquafeed, heat, electricity, and infrastructure resulted the highest sensitivity factors in the investigated impact categories consecutively. With respect to GW, AC, RE, and FF, heat was identified as the most sensitive parameter (SFs = 0.4, 0.5, 0.5, 0.6, respectively). Therefore, the environmental impact mitigation of the cold-weather located system for the aforementioned impacts, which included 4 out of 10 indicators, was most efficient by reducing the impacts associated with heat (e.g., effective space heating, insulation etc.). With respect to OD, EU, and HHNC, aquafeed was shown to be the most sensitive factor (OD SFs = T: 0.7, C: 0.7, H: 0.6; EU SFs = T: 0.9, C: 0.7, H: 0.6; HHNC SFs = T: 0.7, C: 0.5, H: 0.3). Therefore, the mitigation of OD, EU, and HHNC environmental impacts, which incorporated 3 out of 10 indicators, was most efficient by reducing the environmental impacts of the aquafeed that was used in the production system. For example, systems in the locations that are linked to eutrophication (EU) issues could prioritize aquafeed environmental performance improvement (e.g., nutrient uptake improvement, more sustainable ingredient replacements etc.). Regarding PS, electricity was shown to be the most sensitive factor (SFs = T: 0.5, C: 0.4, H: 0.5). Therefore, mitigation of PS impacts associated with the aquaponic system was most effective when mitigating the impacts associated with electricity consumption (e.g., renewable electricity grid, efficient use of natural lighting etc.). This highlighted the importance of elevating clean electricity consumption, especially for urban regions, where photochemical smog is a problem. For HHC and EC impact categories, either heat or aquafeed posed the most SFs among all contributing parameters. This indicated the importance of considering both of the aforementioned parameters for the mitigation of the system's environmental impacts regarding toxicity to the environment (EC) and carcinogenicity to humans (HHC). Despite the traditional assumption of negligible infrastructure impacts (Ayer & Tyedmers, 2009; Ghamkhar, Boxman et al., 2020), the sensitivity analysis of the investigated aquaponic system indicated that the infrastructure could pose a relatively high SF, especially regarding OD, HHC, and HHNC. This emphasized the importance of not neglecting infrastructure and incorporating this parameter within the system boundary in future studies.

3.2 | Economic implications

An economic analysis of the aquaponic system operation under different conditions at different years was performed. The financial parameters associated with the aquaponic system operation are compiled in Tables S4–S8 in the Supporting Information; and the utilized financial indices to perform a comparative economic assessment (NPV, IRR, PBP, and BCR) were explicated in Section S8. The cash flow results with respect to the different processing conditions are tabulated in Table 3. As shown in Table 3, results indicate an economic gain based on C-walleye and H-walleye (2016 and 2017) production data and an economic loss based on tilapia (2015) production data for the investigated aquaponic system. Results

TABLE 3 Financial analysis results for the aquaponic food production

Financial indicator	2015: Tilapia production	2016: C-Walleye production	2017: H-Walleye production
NPV	−$108,785	$35,366	$167,369
IRR	N/A[a]	22%	62%
PBP	N/A[a]	3.96	1.49
BCR	0.47	1.16	1.75

[a]N/A: Not Applicable; net cash flows for all years are negative within the lifespan (net costs > net benefit).

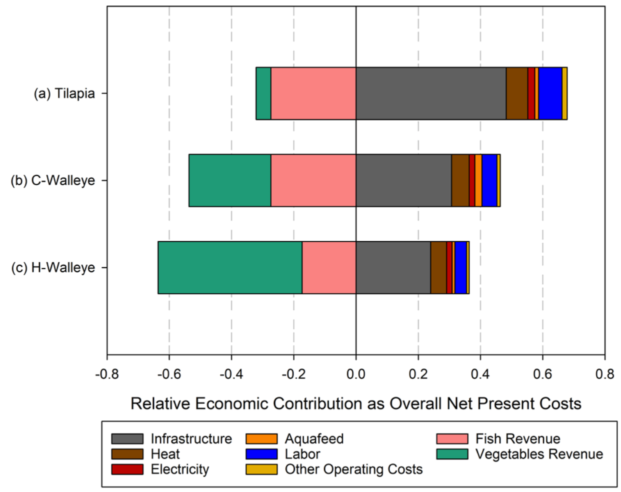

FIGURE 5 Economic contribution analysis for (a) Tilapia (2015), (b) C-Walleye (2016), and (c) H-Walleye (2017) production cycles. Results are harmonized based on infrastructure costs, operating costs, and revenues net present values over the system's lifetime (20 years). Underlying data for Figure 5 are available in Table S9 of the Supporting Information

based on all indices showed the best financial return on investment for the 2017 production, where H-walleye were produced (highest NPV, IRR, BCR and lowest PBP).

By comparing tilapia to walleye production (conventional and hybrid), it was observed that both operating costs and net revenues were increasing. The increase in the operating costs (cash outflows, Δ (NPV) $\approx -\$16$K) was mainly attributed to the higher energy requirements for walleye production cycles (C, 2016 and H, 2017) compared to tilapia production cycle (T, 2015). However, the overall positive cash flow differentiation (cash inflows, Δ (NPV) $\geq \$159$K) outweighed the overall negative cash flow differentiation (Δ (NPV) $\approx \$16$K) by adding on the net fish and plant revenues for walleye production cycles, comparing to tilapia production cycles. The relative favorability of H-walleye production compared to C-walleye production was attributed to elevated revenues for H-walleye production cycle (Δ (NPV) $\geq \$133$K) despite similar infrastructure (Δ (NPV) = 0) and operating Δ (NPV) < $2K) costs. The economic indices utilized in this study on a real-case aquaponic food production system indicated that the practical enhancement of return on investment was dependent on optimization of both cash inflows and outflows (neither could be neglected).

In sum, economic analysis of the investigated aquaponic system revealed that neither of the overall associated benefits or costs could be neglected to achieve elevated net economic profits. However, a detailed evaluation of benefit and cost contributors (contribution analysis) was needed to be performed to obtain precise insights regarding the investigated aquaponic economic implications, and the contributing parameters.

3.2.1 | Contribution analysis

The initial assessment of the economic results highlighted the importance of considering both cash inflows and outflows in the economic assessment of the aquaponic system. However, it did not provide the relative and absolute economic contribution of each parameter. To recognize the economic implications associated with each material and energy-based parameter (in line with what was developed earlier for the environmental implications), a contribution analysis based on net present values (i = 10%, t = 20 years) was performed (Table S9 of the Supporting Information). Results are illustrated in Figure 5.

With respect to the system costs, three parameters contributed to >88% of overall costs for all production cycles, which were infrastructure, heat, and labor. In fact, >66% of the system's costs was attributed to the infrastructure. This highlighted the importance of minimizing infrastructure costs to improve the overall economic performance of the aquaponic system. Grouping infrastructure costs into (1) initial non-replacing (e.g., tanks that are used over the full lifetime) and (2) replacing (e.g., water pumps that are replaced every 7 years) helped to identify prospective steps to minimize infrastructure costs. The initial non-replacing factors resulted an NPV ≈ $15K, while the replacing factors resulted an NPV ≈ $132K. This indicated that the replacing factors contributed 9 times more to the overall costs resulted from infrastructure, compared to non-replacing factors. Improving replacing factors lifespan (e.g., use of more durable lightbulbs, pumps, and in-line heater/chillers) could potentially reduce the overall infrastructure costs.

With respect to the system revenues, both fish and vegetables posed a relatively significant contribution to the net system's revenue (at least 14% and 27%, respectively). In fact, the overall increase of fish and plants production for walleye cycles compared to the tilapia cycle resulted in a transition of net negative net revenue to net positive net revenue, despite the increased operating costs (Table 3).

Similar to what was found earlier regarding the system's environmental performance, the elevated co-production of plants from 2015 to 2016 (Δ NPV from plants ≈ $112 K), and from 2016 to 2017 (Δ NPV from plants ≈ $158 K) was significantly contributing to the improvement in the system's economic performance (summarized in Table 3). Comparing C-walleye (2016) production cycle to H-walleye production cycle, an elevated net economic gain was obtained (Δ NPV ≈ $132 K) despite lower gain from fish production (Δ NPV from fish ≈ -$25 K). However, the increased production of plants had outweighed the decreased production of fish. The large range of plant production quantity from three production cycles and its significance of effect on the total system's revenue (14% for 2015,T; 72% for 2017, H) highlighted the importance of optimizing co-production of plants (e.g., improving operators experience for hydroponic cultivation, selection of most compatible plants etc.) to elevate aquaponic system economic performance.

Leveraging the hotspot inputs from environmental (heat, aquafeed, electricity, infrastructure) and economic (infrastructure, labor, heat) evaluations, the analyses indicated that heat and infrastructure were the two input parameters that need to be prioritized for further investigation to enhance the aquaponic operation favorability, both in terms of environmental and economic dimensions. In addition, the significant effect of (1) labor and (2) plant production amount in economic and environmental performance highlighted the necessity of educating aquaponic operators with the required skills and experiences to optimally operate the aquaponic system, and to maximize systems plant co-production using skillful labor.

4 | DISCUSSION

4.1 | Space heating improvement

Energy demand for space heating is considered to be directly proportional to the Heating Degree Days (HDD) for any specific location and time period (J. Chen, 2019; Jiang et al., 2009). Considering a control level of 23°C, based on the greenhouse building that the aquaponic system was located in, HDDs are illustrated in Figure S1 of the Supporting Information for the investigated aquaponic system (all three year-round cycles) as well as other worldwide locations.

As shown in Figure S1 of the Supporting Information, due to relatively higher HDDs for the investigated aquaponic system compared to warmer locations, the overall space heating requirements are also expected to be comparably higher. Thus, optimizing the total amount of heating requirements could be beneficial by tangibly reducing the overall environmental impacts as well as the total associated heating costs in cold weather climates. Strategies to improve indoor space heating efficiency should be adopted (Bohnes et al., 2018; Ghamkhar, Hartleb et al., 2020). These strategies include: (a) Lowering the heat loss by selecting glazing materials with relatively lower heat transfer (e.g., double plastic film, inflated), (b) Insulating north wall in northern hemisphere locations (south wall in the southern hemisphere), (c) Insulating the lower portion of side walls (e.g., polystyrene insulation), (d) Installing perimeter insulating barrier, (e) Using night curtains to limit night-time heat loss, and (f) Reducing air leaks and infiltration (e.g., wind breaks) (Pade & Nelson, 2005). It is important to mention that the reduction of heating costs is expected to outweigh the higher initial investment costs for the aforementioned strategies to assure economic favorability.

4.2 | Infrastructure improvement

Results of this study highlighted the important role of system infrastructure in the environmental performance and its major role in the economic performance of the aquaponic system. To mitigate the environmental impacts and costs of aquaponic system's infrastructure and equipment per production unit, it is crucial to increase infrastructure's effective lifespan by proper management and operation. Strategies to achieve longer system lifetime include (1) The selection of suitable tank material and size, and (2) Adequate water circulation and aeration.

Despite the compatibility of varying fish tanks to be used in aquaponics, plastic or fiberglass round tanks with flat (or conical) bottoms are preferred, as they have a relatively high lifetime and also facilitate the cleaning process. Regular cleaning of the fish tanks (to get rid of excess food and excrete) will help to extend the systems operation horizon by maintaining infrastructure's quality. In addition, to prevent excessive waste generation, it is important to prevent over-stocking by the choice of appropriate tank size (based on recommended stocking density for different species). Furthermore, effective water circulation and aeration to maintain the aerobic environment is crucial to prevent excessive waste generation through anaerobic organisms and algae growth that can clog to system equipment.

4.3 | Social benefits

The benefits of aquaponic food production systems are not limited to the economic (Bich et al., 2020; Greenfeld et al., 2019) and environmental (Bohnes et al., 2018; Ghamkhar, Hartleb et al., 2020; Jaeger et al., 2019) dimensions. The social outcomes of local aquaponic food production could be profound, following the concepts of industrial ecology in food production (Kendall & Spang, 2020; Niutanen & Korhonen, 2003). The protection of communities' natural ecosystems by producing local favorable food species without resource overuse (Wu et al., 2019), and providing sustainable food production alternatives with potential domestic market benefits (Greenfeld et al., 2019) are two major social benefits associated with aquaponic implementation. Future research could be centered on evaluating the benefits of aquaponics by accounting net social, environmental, and economic benefits. Moreover, case-specific challenges on the industrial-level aquaponic operation, considering different setup factors (e.g., warm-weather vs. cold-weather) could be further investigated.

5 | CONCLUSION

An integrated environmental and economic evaluation of a cold-weather located aquaponic system, considering three operational year-round cycles (tilapia, conventional walleye, and hybrid walleye) was presented in this paper (using LCA and EA). As material and energy inputs and outputs were changing among different years (to adjust the system requirements based on varying environmental and production conditions), the environmental impacts as well as economic implications were consequently different. The major finding of this study can be excerpted as (a) heat, electricity, aquafeed, and infrastructure were the major contributors of the environmental impacts; (b) co-production of plants from the aquaponic system was essential to elevate environmental and economic performance; (c) infrastructure, labor and heat (in terms of costs) were the major economic contributors of the aquaponic system; (d) leveraging both environmental and economic evaluations, results suggest that heat and infrastructure were the two key parameters that should be prioritized for optimal usage in the investigated aquaponic system. Practical approaches to achieve this are: (1) applying effective space heating strategies and (2) extending the system's lifespan through adequate operation and management.

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CONFLICT OF INTEREST

The authors declare no conflict of interest

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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