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Procedia CIRP 69 (2018) 546 – 550

www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Eco-designing Aquaponics: a case study of an experimental production system in Belgium.

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Abstract

Aquaponics is receiving a growing interest as an emerging technology that combines recirculating aquaculture practices and hydroponics to produce fish and vegetables. However, a proper eco-design is essential to limit the environmental burdens and to enhance the economic profitability. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) were here combined to estimate the environmental and economic impacts of a designed pilot indoor aquaponic system in Belgium. Results showed that energy consumption, infrastructure and water consumption represent the main critical issues to achieve both the environmental and economic sustainability of this aquaponic system.

Keywords: Aquaponics, Eco-design, Life Cycle Thinking, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Sustainability

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1. Introduction

In the last 30 years, the scientific community [16], has developed tools to assess the sustainability of food products. To this regard, “eco-design" can be defined as the integration of environmental considerations into a planned or actual productive process in order to improve the resulting products – and possibly to help in the development of new ones – by reducing the environmental burdens throughout their life cycle [4]. One of the most accepted tools to get eco-design information about a process is the LCT approach, subdivided into three types of analyses: LCA, LCC and SLCA. However, while LCA and LCC are internationally accepted tools, SLCA is not totally developed yet. Concerning the aquaculture field, LCT approaches – mostly in the form of LCA – had an exponential growth in the last year, with studies focusing on different species, management condition and rearing systems [1,17,8,23].

However, the eco-design approach has never been applied to aquaponics, that is an innovative practice which integrates the culture of aquatic animals (mainly fish) with the hydroponic production of plants [26]. Aquaponics allows to farm fish and plants at high density, minimizing water consumption and reducing emissions [6,7].

Nomenclature

LCT	Life Cycle Thinking
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
SLCA	Social Life Cycle Assessment
NFT	Nutrient Film Technique
GRP	Glass-Reinforced Plastic
DWC	Deep Water Culture

doi:10.1016/j.procir.2017.11.064

Although this technique seems to be sustainable, neither its environmental nor economic burdens have been deeply investigated as yet: in fact, only few studies are available in literature [2,10]. In the present study, we combined LCA and LCC to analyse the project of a future aquaponic facility located in the "Centre des Technologies Agronomiques" (CTA) in Modave (Belgium), in order to get an overview of its environmental and economic burdens and thus propose less impacting technical solutions prior to its actual building.

2. Material and methods

2.1. System description

The scheme of the pilot aquaponic system is provided in Figure 1 and its technical features reported in the Appendix section (Table A.1). The system will be hosted inside an insulated room constructed in aerated concrete blocks, while fish culture equipment will be composed of 6 rearing tanks. The mechanical filtration will be provided by a drum filter, complemented by a swirl separator. The water exiting the fish culture is conveyed to the mechanical filtering station (swirl separator + drum filter) to remove most of the suspended solids discharged from the system as sludge. Hydroponic cultures are arranged on 3-level shelves lighted by artificial LED lighting. Grow beds will be composed of NFT structures and DWC tanks, with a total surface of 50 m^2. The building is equipped with a double flow ventilation system.

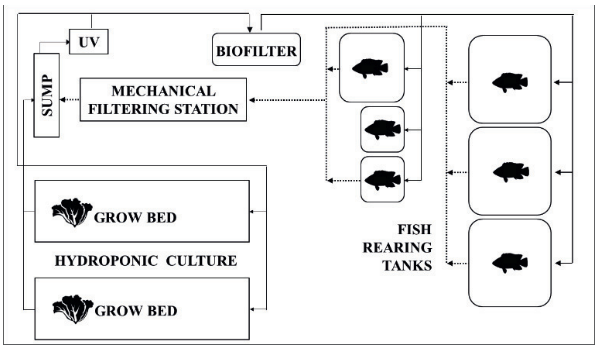

Fig. 1 Scheme of the aquaponic facility. Black arrows show the water flow.

2.2. LCA and LCC

2.2.1 System boundaries and functional unit

The system is designed to farm tilapia (*Oreochromis niloticus*) and lettuce (*Lactuca sativa*) with an expected yearly production of 0.7 and 4 tons of fish and vegetable, respectively. According to Hunkeler et al. [13], LCA and LCC have been performed on the same model of the productive system (e.g. same system boundaries, functional unit, allocation method) and a cradle-to-gate approach was adopted for both the analyses. The processes included in the analysis are the ones taking place within the productive cycle, namely: raw materials (used to build the facility and to run the production), consumptions (energy and water) and transportation. The outputs are represented by the two products (lettuce and tilapia) and their derived wastes (i.e. dead biomass and fish sludge in water) (Figure 2). The functional unit was set as 1 kg of produced lettuce and tilapia was considered as co-product. The allocation was calculated proportionally to the total amount of produced biomass (lettuce = 85.11%; tilapia = 14.89%).

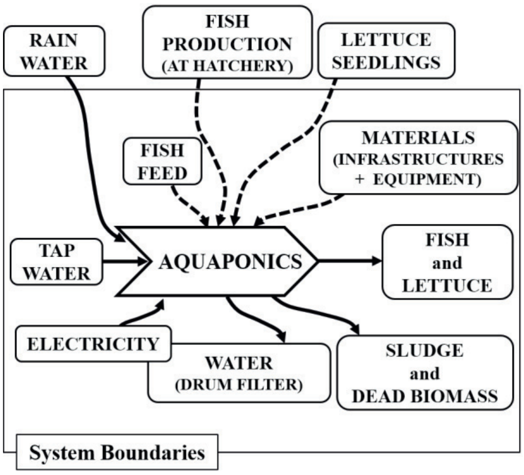

Fig. 2 System boundaries of the considered aquaponic system. Dot arrows indicate processes for which transportation was considered.

2.2.2 *Life Cycle Inventory*

The main system features and consumptions are reported in Table 1.

Table 1. Aquaponic system design and main yearly expected fluxes of energy and matter.

Energy	
Water pumping + LED (kWh)	63,000
Heating (kWh)	15,000
Water	
Input - Tap water (m^3)	870
Input - Rain water (m^3)	200
Output - Water evaporation (m^3)	70
Output - Drum filter backwashing (m^3)	1,000
Production	
Input - Fish feed (kg)	840
Output - Fish production (kg)	700
Output - Plant production (kg)	4,000

Production wastes (dead fish and lettuce) were considered in terms of nitrogen and phosphorous content in the disposed dead biomass, assuming a landfill disposal scenario. Removed suspended solids were quantified in terms of nitrogen and phosphorous released in the sewer system. Concerning LCC, the main inputs are reported in Table 2.

Table 2. Main LCC inputs for the aquaponic system.

SYSTEM EQUIPMENT (euro)		Alarm system	2,000
Pumps (1,100 W)	3,100	Fire door	2,000
Plumbing's	4,500	Steel structures	1,474
Air blower (1,500 W)	2,000	Marine plywood	780
Moving bed biofilter	3,500	Aerated concrete	9,150
Sump tank (1 m^3)	1,500	Other equipment	4,540
Water decanting system (sump + swirl separator)	1,800	Total	63,384
Drum filter (250 W)	5,200	Total (incl. VAT)	76,694
U.V. (120 W)	1,500	**OTHER COSTS (euro)**	
LED lighting	5,040	Building cost	14,750
Water monitoring system (e.g. probes)	4,900	Water cost (euro year^{-1})	4,350
Electric equipment	5,000	Energy cost (euro year^{-1})	10,140
Heating	2,400	Lettuce (euro plant^{-1})	0.06
Ventilation double flux	3,000	Feed (euro kg^{-1})	1.00

2.2.3 Assumptions and limitations

Most of the used data were sourced from the facility project and reflect the equipment which will be actually bought to build up the system. These data were integrated with others derived from literature and experts' judgment. Moreover, some assumptions were necessary (Table 3).

Table 3. Assumptions list.

ASSUMPTION	**REFERENCE**
Lettuces were harvested when reached 300 g.	
Mortality was set at 3% for tilapia.	[15]
Mortality was set at 10% for lettuce.	[3]
Fish faeces production was set at 193.68 g kg^{-1} of feed.	[14]
Tilapia total fillet and carcass (skin + bones) were set at 279.9 g kg^{-1} and 720.1 g kg^{-1}, respectively.	[11]
Total nitrogen and phosphorous percentages in sludge (faeces + uneaten feed) were set at 18.37 and 5.6, respectively.	[22]
Total proteins and total phosphorous in Tilapia fillet were set at 834 g kg^{-1} and 0.03 g kg^{-1}.	[11]
Total proteins and total phosphorous in Tilapia carcass were set at 481 g kg^{-1} and 0.35 g kg^{-1}.	[11]
N and P contents in lettuce were 10.11% and 2.34%.	[12]
Tilapia feed formulation was set according to Situmorang *et al.* [24].	[24]
Infrastructure lifespan was set as 25 years.	
Average transportation distance was set at 30 km for all the supplies.	
Water daily input was assumed to be 1% of the total water volume.	
Tilapia entering the system was considered to be self-produced (CEFRA, University of Liège) and so its cost was set to 0.	

2.2.4 Life Cycle Impact Assessment

For both LCA and LCC analyses, all the fluxes of matter and energy listed in the inventory were then clustered in 5 sub-groups: (i) "Infrastructure" (building + equipment) (ii) "Energy consumption" (iii) "Water consumption" (iv) "Transportation" and (v) "Production" (fish and lettuce + feed + dead biomass + sludge). All the calculations were performed using SimaPro® version 8.0.3.14 [21]. Concerning LCA impact categories, the CML-IA baseline method Version 3.01/World 2000 was used to evaluate Global Warming Potential 100a (GWP) and Eutrophication (EU), while a single-issue method was applied to evaluate the Cumulative Exergy Demand (CExD). LCC was performed following the guidelines stated by Ciroth and Franze [5].

3. Results

LCA and LCC results are reported in Table 4 and Figure 3. The analysis showed that "Energy consumption" represents the main source of impacts for the aquaponic system. In fact, this sub-group accounts for more than 90% of the GWP and CExD impacts and for 46% of EU. For this latter impact category, the "Production" sub-group was found to be responsible of 52% of the total impact. The contribution of "Transportation", "Water consumption" and "Infrastructure" to the overall impacts appears limited.

Table 4. LCA and LCC results. GWP: Global Warming Potential (kg of CO_2 eq); EU: Eutrophication (kg of PO_4^{3-}eq.); CExD: Cumulative Exergy Demand (MJ). LCC expressed in euro.

	LCA			**LCC**
	GWP	**EU**	**CExD**	
Infrastructure	0.75	0.00	11.69	0.78
Energy Consumption	11.99	0.01	222.52	2.16
Water Consumption	0.07	0.00	1.06	0.93
Transportation	0.07	0.00	1.03	0.03
Production	0.25	0.01	2.09	0.35
Total	**13.13**	**0.02**	**238.40**	**4.24**

LCC results show that the total monetary cost referred to the functional unit is 4.24 euro (Table 3). The main economic burden is associated to "Energy consumption" sub-group, responsible of about the half of the whole production cost (Figure 3).

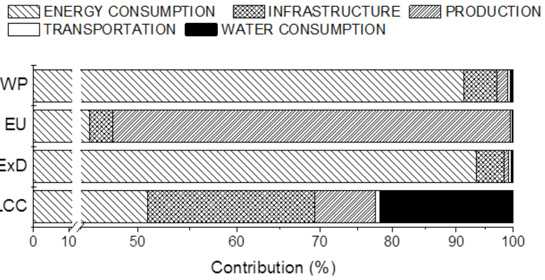

Fig. 3 LCA and LCC results: contribution analysis.

The remaining costs are mainly represented by "Water consumption" and "Infrastructure" sub-groups, each accounting for about 20% of the overall impact. On the contrary the economic burdens associated to "Production" appear to be less relevant (8%).

4. Discussion

The combined application of LCA and LCC showed that energy consumption represents a critical issue to achieve the sustainability of this aquaponic system. About 19% of the total energy consumed would be used to heat water and air representing 12.5% of the energetic monetary costs. Thermic conditioning strictly depends on the farmed species. The growth rate of Tilapia – one of the most used species in aquaponics systems [18] is optimized in a narrow temperature range 28-32°C [8]. Here the growing temperature was considered at 25°C. Since the Belgian electricity mix, according to SimaPro® database (European Life Cycle Database – ELCD – v 3.0), is mainly composed by fossil and nuclear sources, possible improvement could be made by implementing renewable energy sources. Moreover, according to results, the design of the aquaponic system could be reviewed in terms of walls insulation-layer and energetic efficiency of the chosen equipment. However, the major part of energy consumed (81%) is due to water pumping (including the running of the drum filter) and artificial lighting. These impacts seem quite difficult to reduce without rescaling system equipment choosing less "energivorous" solutions. For example, the implementation of sedimentation tanks and/or skimmer can be evaluated to reduce the energy consumption linked to the drum filter.

The contribution analysis underlined the important role of "Production" sub category as impact driver, with a contribution to EU of approximately 55%. These results are in line with previous findings, since both Xie and Rosentrater [28] and Forchino et al. [10] highlighted the important effects of production on eutrophication, mainly due to: (i) fish-feed; (ii) the disposal of wastes in landfill and sewer system.

"Infrastructure" accounts for around 5% of the GWP and CExD impacts and represents up to 18% of the economic costs. In this case, improvements could be done by choosing less expensive equipment, without compromising the system performances.

Concerning water consumption, the system here analysed requires about 1,070 m^3 year^{-1} with an estimated hydric consumption of 0.3 m^3 per kg of lettuce. This value is more than 10 times higher if compared to the one calculated by Forchino et al. [10] for a small scale aquaponic system. In our case, this difference is essentially due to the use of a drum filter, which requires more than 90% of the overall hydric consumption. Moreover, if the LCA analysis showed that the consequent effects on the environment are not that high, water consumption represents an important source of impact for LCC, contributing for 22.6% to the total cost.

Given the adopted approach, further argumentations on the economic feasibility of the facility are merely conjectures, since neither operating costs nor market prices were considered.

However, some considerations can be made. LCC seems to suggest that the production cost of lettuce will be markedly higher than in conventional systems. Organic food is perceived as more healthy and tastier than its equivalent produced with the conventional system [20] and consumers are generally neutral or favorable to aquaponics [25] but it is not sure whether they will be willing to pay higher prices for this kind of products. Therefore, market research is recommended to determine consumers' perception, so to avoid an investment on an unprofitable species. Tilapia grows quickly and requires low operating costs, but needs warm water and it is not well known in Europe, conversely to Asian and North American markets. For instance, tilapia farmed in Egypt is generally sold without any value addition at the wholesale market [9]. However, while tilapia has an unsure market potential for Belgium, lettuce is a suitable product for aquaponics, since this species can be easily cultivated with this technique [18] and it appears to be in line with the European market demand [19,27].

5. Conclusion

The research here conducted provided an overview of the strengths and weaknesses of the facility prior to its actual construction. Results indicated that drum filter strongly affects the economic expenses by consuming a huge amount of energy and water: therefore, designing a system with a less energy and water demand component could increase the sustainability of fish and vegetables produced via aquaponic. In conclusion, the present study proves the importance of LCA and LCC as eco-design tools, helping in both improving system performances and reducing the relative economic and environmental burdens.

Acknowledgements

This work was supported by the COST Action FA1305 (The EU Aquaponics Hub: Realising Sustainable Integrated Fish and Vegetable Production for the EU), the EMFF (European Maritime and Fisheries Fund) and Wallonia (SPW-

DGO3). We are grateful to Christian Prignon, Denis Gustin and Laurent Minet for their participation in the system design.

Appendix A

Table A.1. Aquaponic system: technical features

AQUAPONIC SYSTEM: TECHNICAL FEATURES		
Building	Material	Aerated concrete, thermal transmittance U=0.31 W m^{-2} K^{-1}
	Room dimensions	14.6 x 7.1 x 3.5 m
	Room total surface	103.66 m^2
	Room total volume	362.8 m^3
Recirculating Aquaculture System	Fish tanks (n= 6)	GRP, total volume 6.4 m^3
	Sump tank (n= 1)	GRP, total volume 1 m^3
	Drum filter	30 m^3 h^{-1}, 250 W
	Backwash pump	1 kW
	Moving bed biofilter	1.5 m^3
	Circulation pump	1.1 kW
	Air blower	1.5 kW
	UV sterilizer	95 W
	Electrical heating	9 kW
	Swirl separator	GRP, total volume 3 m^2
Hydroponic Deep Water Culture	Grow beds - DWC	Wood and liner, total surface 33.3 m^2
	Grow beds - NFT	Alluminium, 16.7 m^2
	Lighting	LED, 6 kW

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