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Profitability of multi-loop aquaponics: Year-long production data, economic scenarios and a comprehensive model case

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Abstract

This case study examined the productivity and economic performance of a double recirculation aquaponic system in Germany with a total interior area of about 540 m^2. Calculations were carried out as an ex post analysis based on one-year production data. The initial situation was not profitable; therefore, two scenarios were developed, which envisaged a significantly improved productivity of the fish as well as of the plant unit and a more than threefold enlargement of the greenhouse to make maximum use of the fish effluent. An ex ante analysis was performed and showed that the second scenario was profitable with a payback period of about 12 years. On the basis of this scenario, a simple but comprehensive model case with the complete set of economic key indicators showed that aquaponics is feasible if it exploits its potential, regardless of the high initial investment costs. The model case would cover an overall space of about 2,000 m^2, which is suitable for professional aquaponics in urban and peri-urban areas with their limited space availability. Furthermore, multi-loop aquaponics with its inherent circles fits into the circular city concept and implements resource-efficient and sustainable food production into the urban fabric, which is important with increasing urbanization.

KEYWORDS

case study, comprehensive model case, economic scenarios, professional aquaponics, profitability analysis, urban agriculture

1 | INTRODUCTION

Considering current problems like climate change, population growth, urbanization as well as overexploitation and pollution of natural resources 'global food production is the largest pressure caused by humans on Earth, threatening local ecosystems and the stability of the Earth system' (Willett et al., 2019). Consequently, there is an urgent need to find solutions for sustainable and efficient food production solutions to cope with the consequences of these issues (D'Abramo & Slater, 2019).

Coupling the production of aquatic animals (e.g. fish) and plants (e.g. vegetables) forms the basis for aquaponic systems where wastewater from the aquaculture section is used for the nutrition of plants. Thus, a resource-saving food production is enabled, especially concerning water and nutrients, which has a reduced impact on ecosystems compared to a stand-alone greenhouse or a stand-alone fish production system. This sustainable farming technology received growing attention during the last years (Goddek et al., 2016; König, Junge, Bittsanszky, Villarroel, & Kőmíves, 2016; Monsees, Kloas, & Wuertz, 2017). Despite the fact that aquaponics has potential for a sustainable development of the food sector, it is still a niche market (Goddek et al., 2019). In 2017 about 1,113 kt fish and fish products were consumed in Germany (Fischinfo.de, 2019) but only 19.2 kt fish were produced in German aquaculture with 2.7 kt derived from closed recirculating aquaculture systems (RAS) (Destatis, 2017). This means that only 2.4 ‰ of the fish and fish products consumed originate from RAS. Even if the share of aquaponics among RAS in 2017 is unknown, it is obvious that the fraction of aquaponics—which is highly linked to RAS—is only trifling.

One reason for its low usage might be the uncertain economic outcome of aquaponics. Only a few publications are recently available dealing with economic aspects in detail, one of them stating that 75% of enterprises in the United States are small and had sales of less than 25,000 USD per year (Engle, 2015). An international survey among aquaponics practitioners supported these statements and also pointed out that the majority of aquaponic systems are still represented by smaller farms (Love et al., 2015). Main obstacles for commercial aquaponics are the high initial investment costs and especially in Germany the high operating costs for fish feed, labour and energy (König et al., 2016) as well as the necessary expertise in both aquaculture and horticulture (Bosma et al. 2017). Furthermore, the margin depends on the market environment and the production risks which are difficult to forecast. In general, aquaponic production systems are already well described in several scientific publications (Naegel, 1977; Rakocy, Masser, & Losordo, 2006; Rennert, Groß, van Ballegooy, & Kloas, 2011), but due to confidentiality reasons real economic values derived from commercial farms are still scarce, especially covering a period of a year. ‘There is still a long road ahead for the sound economical assessment of aquaponics’. (Turnšek et al., 2019).

Classical aquaponics couples fish and plant production in a single recirculation system (Rakocy, 2012) but cannot ensure optimal production parameters simultaneously for fish and plants due to the fact that they need, beside others, different pH values (Kloas et al., 2015). In the case of severe fish diseases or pest outbreaks, the range of countermeasures is limited, because, for example, fish pathogens have to be removed from the plant unit and on the other hand pesticides are often toxic for fish. These problems were overcome by double recirculating aquaponic systems (DRAPS), wherein RAS and hydroponic system (HS) are coupled unidirectional but maintain separate water cycles (multi loops) in both production units (Kloas et al., 2015). DRAPS allows a RAS optimized for fish production safeguarding animal welfare (Baßmann, Harbach, Weißbach, & Palm, 2020; Monsees et al., 2017), and for the HS, an independent regulation of pH and the dynamic adaptation of nutrient concentrations are possible (Kloas et al., 2015). The latter is relevant especially for plants with high nutrient requests, such as tomatoes. Otherwise, this approach may mislead farmers to rely too much on external fertilizer, lowering the contribution of nutrients from aquaculture down to 50% (Lennard & Goddek, 2019). For professional applications, it is important that DRAPS enables equal productivities for fish compared to conventional RAS (Monsees et al., 2017) and plants compared to single HS (Delaide, Goddek, Gott, Soyeurt, & Jijakli, 2016; Suhl et al., 2016). Nota bene: DRAPS is sometimes denoted as decoupled aquaponic system (Goddek et al., 2019), but it is not without criticism (Lennard, 2017).

This concept was tested and evaluated under practical/commercial conditions (INAPRO, 2018), and a schematic overview was published (Karimanzira, Keesman, Kloas, Baganz, & Rauschenbach, 2017). One aquaponic demonstration facility was located in Waren, MV, Germany. The construction and operation were partly project-funded and partly financed by in-kind contributions of both the constructor and the operator. This facility was not expected to run profitable without funding, it rather should provide reliable, realistic data to determine the production conditions and outcomes of a scalable facility for DRAPS.

The present study had three goals concerning aquaponics: (a) To deliver a short report of a real facility's initial situation together with ex post economic calculations based on year-long production data. (b) To show by means of two scenarios how to improve the economic performance by (i) assuming a distinctly increased productivity of the fish as well as the plant unit and (ii) optimizing the transfer of RAS wastewater to the HS through a greenhouse extension. (c) To develop a comprehensive model case of a stand-alone aquaponic facility with its main economic figures.

For the examination of profitability of both scenarios and the model case, ex ante profitability analyses were performed which are presented and discussed. As an outlook, the application of aquaponics in an urban context was debated, bringing sustainable food production into the city as a kind of a resource-efficient urban and peri-urban agriculture (CITYFOOD, 2019).

2 | MATERIAL AND METHODS

2.1 | Initial situation

The aquaponics in Waren (DE) was built as a part of the already existing fishery company Fischerei Müritz-Plau GmbH, which is a small-to-medium enterprise (SME). The new facility follows the controlled-environment agriculture (CEA) approach and consists of a Venlo-type lightweight shell (von Zabeltitz & Meyer, 1985) which covers a total interior area of 538 m^2 and houses the RAS in an opaque section (124 m^2), the greenhouse (352 m^2), feed storage (18 m^2) and technical installations (44 m^2). A slaughter room, a salesroom, an office and a social room did already exist at the fishery enterprise and were thus not included in the construction. The operation of the RAS started in 2016, and the amounts of fish and tomato sales were collected on a monthly base. Data were recorded over the span of a whole year, including all phases of the production cycle, from June 2017 to May 2018 which was regarded as the initial situation (InitS) of the Waren facility.

For rearing African catfish (*Clarias gariepinus*), the RAS unit consists of 12 rectangular fish tanks, each with a volume of 2.2 m^3, resulting in a productive water volume of about 26.4 m^3. The average weight of the fingerlings was 2% of fish yield weight, the loss of fish accounted to 3% of the yield weight per batch, and the average feed conversion ratio (FCR) was 1.15, including the feed and fish losses. The tanks have an outlet placed at the bottom of each tank constructed as a double-walled pipe to remove faeces and leftovers from the bottom. The amount of water which flows through the tanks can be adjusted by a ball valve. Behind the fish tanks, two sedimentation tanks are placed for a mechanical water treatment. Each sedimentation tank has a water volume of 1.6 m^3. During the further recirculation, the water is UV-disinfected for reducing pathogens before reaching the pump sump. From here, the water is pumped to the top of the trickling filter (31 m^3), a bioreactor which transforms the fish-toxic ammonia and ammonium over nitrite to nitrate by nitrifying bacteria.

The HS in Waren uses 320-m^2 net-acreage of the 352-m^2 greenhouse area. It employs 320-m trenches and applied two different irrigation technologies to compare their usefulness (Suhl et al., 2016). At 50% of the trenches, nutrient film technology (NFT) was installed whereas the other 50% of the trenches were equipped with a drip irrigation system. To keep the growing system simple and to remain within the available project budget, some trade-offs had to be made. Therefore, due to predictable energy demand for greenhouse heating, a plant production winter break took place during November and December which was mainly used for disinfection and maintenance work. Likewise, no CO_2 fertilization was applied. To prevent higher temperatures that may have put the production at risk, the greenhouse was temporarily cooled by vapour compression chillers. The tomato production in Waren lasted from January to October but started late in January 2018 because of an insufficient availability of new plants.

At the Waren facility, there were powerful electric grid and gas connections but no district heating available. Due to the fact that heating of the RAS process water is required for African catfish and heating of the HS is necessary during longer periods of the year, a gas based combined heat and power unit (CHP) was installed. The CHP device is heat-demand controlled and has a maximum of 16-kW electricity output forming the main electricity supply. It is supported by photovoltaic power (12 kW peak) which generated additional electricity especially at times when cooling for the greenhouse was needed. In case of not internally used electric energy, these two components contributed to the system output as surplus electricity sales. The power grid was used only during no-heating and no-sunshine periods.

2.2 | Two scenarios

To analyse the facility's profitability under extended operation, two scenarios were developed and analysed (cf. Table 1). To ensure realistic estimations and to facilitate the comparability, some figures of the InitS were used for the two scenarios. Where appropriate, the parameters of the scenarios were checked against the specifications of the German agricultural organization 'Kuratorium für Technik und Bauwesen in der Landwirtschaft' (KTBL: Frisch, 2017). Nota bene: This paper uses the SI unit 'a' for annum and the SI accepted unit 't' for metric ton (NIST 2019).

TABLE 1 Overview of the boundary conditions concerning the three cases

		InitS	ScenA	ScenB
RAS	Volume	1	1	1
	Yield	1	**1.64**	**1.64**
with CHP	Investment €	345,600	345,600	345,600
HS	Area	1	1	**3.44**
	Yield	1	**2.46**	**8.46**
	Investment	1	1	**2.66**
	Investment €	103,226	103,226	275,000
SUM	Investment €	448,831	448,833	620,617

The bold values is to emphasize important statements.

Based on the existing aquaponic configuration of the InitS, a Scenario A (ScenA) was build assuming a distinctly improved productivity to reach the full production potential of the RAS as well as of the HS. An optimized production cyclogram, being a theoretically based staggered RAS production model (Ralf Georg Jahnke, Autosoft, unpublished), indicates that this RAS has the potential to produce 24 t African catfish. This number was reduced by 10% to 21.6 t to keep the calculation more conservative and to take uncertainties such as losses into account. Based on own experiences, a slightly improved FCR of 1.09 was assumed. ScenA considers a higher productivity of the plant unit too, because at the InitS the potential of tomato production has not been fully exploited according to KTBL (KTBL: Frisch, 2017) and to our own experiences. Within the same project, Inagro in Belgium conducted semi-commercially scaled experiments by connecting two already existing RAS/HS systems to a functional aquaponics and proved the possibility to achieve tomato yields of 53 kg/m^2a by optimized production management and nutrient utilization involving experienced horticulturists (INAPRO, 2018). A yield of 53 kg/m^2a corresponds with the KTBL specification for German greenhouses with CO_2 and without illumination. Without $CO_{2,}$ the prospective yield was reduced to 41 kg/m^2a in ScenA, still two and a half times the tomato productivity of the InitS (cf. Table 2). The water consumption was assumed to be 30 L/kg tomatoes being higher than 18 L/kg as proposed by the KTBL specifications (KTBL: Frisch, 2017). The increased productivity in ScenA does not require more heating energy by using the same HS area; thus, the sale of CHP-generated electricity remains constant in that scenario.

A second Scenario B (ScenB) was configured by extending the greenhouse size of ScenA in order to maximize the utilization of the nutrient-rich fish wastewater for plant irrigation and to minimize the environmental impacts by aquaponic facility wastewater. Within ScenA, the fish production has reached its full potential and thus the RAS parameters remain the same for ScenB, being the starting

TABLE 2 Costs and benefits of the initial situation and both scenarios

	Initial situation Jun 2017–May 2018				Scenarios			
		InitS			**ScenA**	**ScenB**		
	Data source	**recorded**			**estimated**	**estimated**		
Boundary conditions								
RAS/HS	Facility [€]	448,831			448,833	620,617		
RAS	Fish tank volume [m^3]	26.4			26.4	26.4		
	Feed conversion ratio	1.15			1.09	1.09		
	Fish yield [kg/a]	13,200			21,600	21,600		
	Fish price [€/kg]	2.50			2.50	2.50		
HS	Net-acreage [m^2]	320			320	1,100		
	Tomato yield [kg/m^2a]	16.7			41.0	41.0		
	Tomato yield [kg/a]	5,332			13,120	45,100		
	Tomato price [€/kg]	3.50			3.50	3.50		
RAS/HS	Harvest ratio	1:0.4			1:0.61	1:2.09		
Costs		€	ct/kg[a]	%	€	€	ct/kg[a]	%
RAS	Gas, electricity	7,370	56	20	7,370	7,370	34	16
	Water	1,561	12	4	1,561	1,561	7	3
	Fingerlings	1,778	13	5	2,909	2,909	13	6
	Fish feed	12,816	97	35	19,912	19,912	92	42
	Fish feed transport	928	7	3	1,519	1,519	7	3
	Labour	10,938	83	30	12,438	12,438	58	26
	Equipment, repair	1,061	8	3	1,061	1,061	5	2
	Consumables	270	2	1	442	442	2	1
	Total	36,721	278	100	47,211	47,211	219	100
HS	Gas, electricity	9,471	178	28	9,471	21,783	48	22
	Water	299	6	1	359	469	1	0
	Tomato plants	826	15	2	826	2,838	6	3
	Plant protection	501	9	2	501	1,722	4	2
	Fertilizer	547	10	2	821	2,822	6	3
	Labour	20,313	381	61	35,313	65,313	145	66
	Equipment, repair	1,061	20	3	1,061	3,647	8	4
	Consumables	270	5	1	270	928	2	1
	Total	33,286	624	100	48,621	99,522	221	100
Benefits								
RAS	Fish sales	32,964	250	51	54,000	54,000	250	24
HS	Tomato sales	18,662	350	29	45,920	157,850	350	70
RAS/HS	Electricity sales	12,432		19	12,432	12,432		6
	Total	64,058		100	112,352	224,282		100
Balances								
RAS	Benefits—Costs	−3,757			6,789	6,789		
HS	Benefits—Costs	−14,624			−2,701	58,328		
RAS/HS	Benefits[b]—Costs	**−5,950**			**16,520**	**77,548**		
Simplified ROI[c]			−1.3%		3.7%	12.5%		
Payback period		-			**27 a**	**8 a**		

The bold values is to emphasize important statements.

[a]Fish, tomato.

[b]Including electricity sales.

[c]Without depreciation, interest and taxes.

point for scaling up the ScenB HS net-acreage. The RAS needs in both scenarios 1,419.1 m^3 fresh water to exchange process water, so 118.3 m^3/month fish wastewater can be potentially transferred to the HS (as transfer water) to irrigate and fertilize the plants. This potential is not exhausted because no water demand exists during the plant production winter break. A simple transfer water model was developed to estimate an optimal HS net-acreage under these conditions assuming a plant uptake of 535 L/a. With 2.3 plants/m^2, this net-acreage was found to be 1,100 m^2 leading to an overall HS water consumption of 1,350 m^3. This resulted in a maximization of transfer water (1,006.5 m^3) while simultaneously minimizing the additional HS fresh water requirement (343.5 m^3) and the RAS portion of the facility wastewater output (412.6 m^3). Regarding this approach, the main assumptions of ScenB compared to ScenA are (a) a more than tripled greenhouse size, while (b) maintaining the tomato productivity of 41 kg/m^2. The net-acreage of the greenhouse is increased by 3.44 in ScenB compared with InitS. It is assumed that the higher plant production in ScenB can still be absorbed by the market. Because of the surface-to-volume ratio, the heat radiation of the greenhouse will not increase linearly with the area, and for the less compact building shape, a heat radiation scaling factor of approximately 2.3 was calculated. In terms of the energy balance, the CHP parameters in ScenB are the same as in ScenA for a better comparison of the scenarios. The additional heating and cooling sources for the extended greenhouse are assumed to be installed by extra non-CHP equipment and considered in the investment costs calculation.

2.3 | A model case

The InitS and the derived scenarios, ScenA and ScenB, are embedded in the infrastructure of an existing enterprise; thus, the economic values cannot simply be applied to other use cases. To close this gap, the main economic figures of a fully functional stand-alone aquaponics are proposed as a model case (ModelCase). This ModelCase uses ScenB but (a) waives the CHP and the cooling of the greenhouse and (b) additionally features a slaughter room, a salesroom, an office and a social room to be fully functional. The annuities for the facility investment are taken as rounded values from ScenB, even if these changes probably reduce the investment. The size of the ModelCase would be below 2,000 m^2 base area when adding those properties.

The ModelCase is based on the following assumptions: (a) steady production with year-round RAS utilization and a HS winter break, resulting in annual outcomes comparable to ScenB, as well as (b) complete and (c) direct sales of the produced goods. Figures available in ScenB were rounded and if applicable adjusted to reference values. Figures not available in ScenB were derived from the, respectively, cited sources: talks to experts, literature or similar sources or estimations based on own results. Provisions for production risks were not included. The costs for the fish feed include the expenses for its transport. Costs for labour are split according to qualifications (worker, engineer, management) and the working costs for fish processing and sales of fish and tomatoes are listed separately. Costs concerning the operation support comprise maintenance and repairs, consumables and processing expendables for fish and tomatoes. Other costs are generated by advertising, the online shop, insurances, veterinary and others including external services, fees, transportation and disposal of residues.

2.4 | Profitability analysis

A cost–benefit analysis (CBA) is a systematic process that can be used for calculating and comparing costs and benefits of an investment or a project and subsequently determine the net benefits of the proposal relative to the status quo (Boardman et al. 2017; Marshall, 1890). This study uses some of the CBA methods to perform a profitability analysis (PA) which is divided into four sections: boundary conditions, costs, benefits and balances. All the important assets are listed and the economic figures are net values. The prices used in the scenarios are those of the InitS, and inflationary effects were not considered and the annual gross margin of the facility was calculated as the difference of benefits and costs. Electric energy sales from the CHP and the photovoltaic were not split between RAS and HS. To underline the coupling of the two production processes (fish/plant) in aquaponics, the concept of a functional unit is used, where one kg of produced fish is linked together with the correspondingly produced amount of tomatoes. The PA was built on a spreadsheet to provide an easy to handle and adaptable tool and did not use a function-based economic model (Karimanzira et al., 2017).

An economic performance measure is the return on investment (ROI), the ratio between the annual profit and the cost of investment. Its reciprocal gives the payback period that is the time an investment needs to reach the break-even point. Economic feasibility of a scenario over time is given, if the time of amortization is less than the assumed operation life time which is set to be at least 15 years. In this study, a simplified ROI without depreciation, interest and taxes was used to compare the scenarios. The financial investment necessary for the Waren facility (InitS) as well as the expenses for the first year was partly project-funded (INAPRO, 2018) and the land was available and did not have to be acquired, that means no loans were required to finance the facility and its operation. The investment of ScenA was inherited from the InitS and the investment of ScenB was extrapolated likewise without crediting; thus, the gross profit for all three cases was calculated without depreciation and interest. The hereupon determined payback period is related to the project conditions, considers no imponderabilities concerning the operation and is rounded to a whole year (cf. Table 2).

In contrast to the described facility, most aquaponics will be debt financed. To present a corresponding example, ScenB was supplemented with investment calculations based on annuity loans for the facility, the land (2,000 m^2, 15 €/m^2) and the first-year operating costs. The German credit institute 'Landwirtschaftliche Rentenbank' offers different agriculture promotion programmes and the conditions of the programmes A 243 for the facility, D 244 for land and first-year operation costs HS, and D 291 for first-year operation costs RAS, were applied to ScenB to calculate the necessary loans (LW-RB, 2019). The profit was set against the annual annuity payments to proof the financial feasibility of this scenario, and a hypothetical payback period was calculated for the break-even of the accumulated profit and the pending annuity of the loans. An external investor would evaluate the project by, for example, the discounted cash flow, a method considering the net present value of future cash flows. Over the term of the loans, production and distribution are planned to remain constant. The annuities already consider implicitly the time value of money; thus, the cash flows are static and will not change over the years, apart from inflation, which is not taken into account here.

3 | RESULTS

3.1 | Initial situation

The live weight fish yield of the InitS was 13.2 t, and 1,419.1 m^3 input water per year was necessary to exchange the RAS process water resulting in 107.5 L per kg fish. The fish production started with suboptimal performance and only two tanks per batch with a final stocking density up to 300 kg/m^3 at harvest time. The annual operation costs of the RAS were 36,721 € at the InitS. The average price for fish feed was 86.3 ct/kg and this amounted to 12,816 € (35%) per year, the highest single position among the RAS costs and thus 97 ct had to be expended for each kg fish produced. The facility was run by a single employee and the entrepreneur of the aquaponic facility reported costs of 31 k€ for work labour without differentiating this figure, but estimated that 35% was related to the RAS at the given configuration of the facility which was with 10,938 € the second highest position among the RAS costs. The Waren aquaponic entity is part of the Fischerei Müritz which processes the fish and the tomatoes and sells the food at an onsite market shop. There were no selling records of the company available and the costs for processing the fish remained unknown. The internal average price at the RAS farm gate for the complete unprocessed fish was vaguely reported to be 2.00 €/kg but was more likely 2.50 €/kg, still below the break-even price of 2.78 €/kg. The internal benefits of the InitS from fish sales were 32,964 €. Since tomato production started late in January 2018, it remained relatively low with a peak of 1,408 kg/month in June (cf. Figure 1) and an average tomato yield of 16.7 kg/m^{2}a fresh matter leading to an overall harvest of 5,332 kg. The annual operation costs of the HS were 33,286 € at the InitS, including 20,313 € for work labour, which contributed to nearly two third (61%) of the HS costs. The consumer price for tomatoes fluctuated between 3.0 €/kg and 5.5 €/kg over the year and the company reported an internal average price of 3.5 €/kg tomatoes which resulted in an overall benefit of 18,662 €.

Additionally, the CHP and PV generated surplus electric energy was sold at the respective market price and gained 12,432 €. The economic results of the InitS revealed that the operation of the facility caused overall losses of 5,950 € (cf. Table 2, InitS) meaning that the production of a functional unit of food generates losses of 0.45 € with each kg of fish and the respective 0.4 kg of tomatoes (cf. Table 3).

3.2 | Scenario A and B

Since the productivity of the RAS operation in Waren (DE) achieved a considerable advancement, it switched from two to three tanks per batch with a stocking density up to 300 kg/m^3 in December 2018. This has proved that the target value of 21.6 t for ScenA is realistically reachable. The amount of water to produce 1 kg fish was reduced from 107.5 to 65.7 L/kg, a demanding but realistic goal (Martins et al., 2010; Martins, Ochola, Ende, Eding, & Verreth, 2009; Verdegem, Bosma, & Verreth, 2006). Despite the increased production in ScenA, the amount of exchange water (1,419.1 t) was equal to InitS and no additional gas consumption for water heating was required. The annual operation costs of the RAS in ScenA were 47,211 € with increased costs for fingerlings and fish feed according to the 1.64-fold productivity. The labour did not increase at the same rate as the productivity, but additional 10% full-time equivalent (FTE) part-time labour was required. With 19,912 €, fish feed was still the highest single cost position (42%) followed by RAS labour with 12,438 € (26%). For ScenA, an increase of the HS productivity by a factor of 2.46 was assumed. The necessary labour was covered by one part-time FTE, and the costs per one kg tomatoes decreased from 6.24 € in InitS to 3.71 € in ScenA. The total costs of the HS aggregated to 48,621 € and the most important positions were HS labour with 35,313 € and gas/electricity with 9,471 €. The revenue from fish harvest in ScenA accounted to 54,000 € and the tomatoes generated a revenue of 45,920 €. The energy sales in ScenA

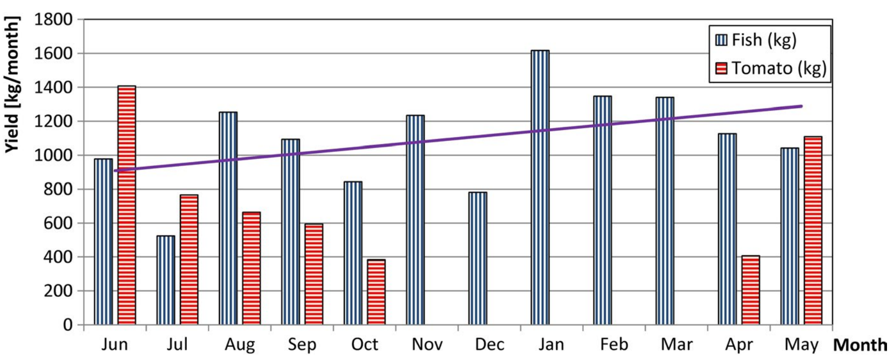

FIGURE 1 Fish and plant harvest per month at the aquaponics Waren (DE), June 2017–May 2018; the line depicts the increasing trend of the fish production [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Losses and profits per functional unit

		InitS	ScenA	ScenB
Product		per kg	per kg	per kg
	Fish	−0.28 €	0.31 €	0.31 €
	Tomatoes	−2.74 €	−0.21 €	1.29 €
Functional unit (FU)		per FU	per FU	per FU
	Tomatoes per kg fish	0.4 kg	0.61 kg	2.09 kg
	FU incl. Energy sales	**−0.45 €**	**0.76 €**	**3.59 €**

The bold values is to emphasize important statements.

did not change compared with InitS. Together with the electricity sales, the total income from RAS and HS accounted to 112,352 €. Considering the costs, the overall result of ScenA showed a positive result of 16,520 €.

In ScenB, the annual RAS costs were the same as in ScenA. The costs required for operating the extended greenhouse were assumed to be 99,522 €, ca. three times the respective amount of the InitS, with labour (65,313 €) as the major share. Selling tomatoes gained 157,850 € in ScenB based on the average price from the InitS. The operation costs of ScenB led to 77,548 € gross profit (without loan and before taxes). The energy sales did not scale up and remained constant in both scenarios but the relative income from surplus energy sales was reduced in parallel from 19% in InitS to 6% in ScenB.

3.3 | Comparison of the regarded scenarios

The most important changes of the boundary conditions of both scenarios relative to the InitS were (1) the increase of RAS productivity by factor 1.67 in ScenA and ScenB, (2) the increase of HS productivity in ScenA by factor 2.46, and (3) the additional increase of HS net-acreage by factor 3.44 in ScenB which simultaneously increased the required HS investment costs by a factor of 2.66 (cf. Table 1). According to the simplified payback period calculation, the InitS would never reach amortization and the payback period of ScenA would be around 34 years. However, yields of 21.6 t fish and 45.1 t tomatoes lead to a profitable balance in ScenB, and without depreciation, interest and taxes a payback period of around 8 years could be achieved (cf. Table 2).

Concerning the cost structure, fish feed had the main cost share in all cases in RAS with 35% in InitS and 42% in ScenB, whereas labour as the main cost driver in HS increased its share from 61% in InitS to 66% in ScenB, the respective figures are given in the section 'Costs' of Table 2. From the sales point of view, the InitS made 0.28 € loss per kg fish and 2.74 € loss per kg tomatoes. These results were turned around in ScenB, where fish gained 0.31 € and tomatoes gained 1.29 € per kg (cf. Table 3). Under the condition of a winter break in the plant production, the fish/tomatoes harvest ratio increased from 1:0.4 in InitS over 1:0.61 in ScenA to 1:2.09 in ScenB. The overall result per functional unit (one kg fish together with the respective amount of tomatoes) was −0.45 € in the InitS, 0.76 € in ScenA and 3.59 € in ScenB (cf. Table 3).

For the InitS, an investment of 448,830 € was required. The same was also set for ScenA because the core idea of this scenario was an increased productivity within the configuration of the InitS. The investment for ScenB was assumed to be significantly higher with 620,615 € due to the additional investment costs for the greenhouse extension. The latter one caused an increase of the HS investment of 171,774 € changing from 103,226 € in the InitS to 275,000 € in ScenB (cf. Table 1).

For ScenB, the annuity payment accounted to 60,924 € with 82% share for the facility, 16% share for the first-year operating costs and 2% share for the land (2,000 m^2, 15 €/m^2), but this credit would have a longer period of 30 years (cf. Table 4). A hypothetical payback period would be 11.8 years for the whole investment including the first-year operation (compared with 8.0 years without loans). Because the credit conditions were fixed, the real payback period was 15 years and the remaining profit could be used to cover the

TABLE 4 Estimation of the financial result of Scenario B including interest

Investment Scenario B (ScenB)	Credit	Rate	Years	Annuity	
Facility	620,000 €	1.45	15	49,848 €	82%
Land (2,000 m^2, 15 €/m^2)	30,000 €	1.75	30	1,332 €	2%
First-year operating costs	140,000 €	1.60	15	9,744 €	16%
Sum	**790,000 €**			**60,924 €** (s)	**100%**
Annual values					
Operation balance	77,548 €				
Annuity payment	−60,924 €				
Result Scenario B	**16,624 €** (r)				
Payback period (PP)			PP = 15−(15 * r)/ (s + r)		
PP hypothetical	**11.78 a**				

The bold values is to emphasize important statements.

TABLE 5 Annual costs of the ModelCase

	RAS		HS		Aquaponics	
Costs	Amount	€/Unit	Amount	€/Unit	Result €	%
Fish						8.6%
Fingerlings [pcs]	15,800	0.19			3,002	
Fish feed [kg]	23,000	0.91			20,930	
Plants						2.2%
Tomato plants [pcs]			2530.00	1.11	2,800	
Plant protection [m^2]			1100.00	0.45	500	
Fertilizer [m^2]			1100.00	2.55	2,800	
Energy						10.8%
Gas [kWh]	112,000	0.018	440,000	0.018	10,036	
Electricity [kWh]	29,000	0.28	42,000	0.28	19,880	
Water						0.9%
Tap water [m^3]	1,400	1.10	350	1.10	1,925	
Wastewater [m^3]	400	1.50	0	1.50	600	
Labour						41.5%
Worker [FTE]	0.4	15,000	2.7	15,000	46,500	
Processing, sales [FTE]	0.2	15,000	0.6	15,000	12,000	
Engineer [FTE]	0.2	37,000	0.8	37,000	37,000	
Management [FTE]	0.2	50,000	0.2	50,000	20,000	
Operation support						6.7%
Maintenance, repairs	1	1,000	1	3,500	4,500	
Consumables [m^2]	140	8	1,100	0.30	1,450	
Processing [kg]	9,245	0.50	39,900	0.20	12,603	
Other						7.2%
Advertising		-		-	8,000	
Online shop	1	7,000			7,000	
Insurances, veterinary, etc.		-		-	5,000	
Annuities, lease or rent						22.1%
Facility		-		-	50,000	
Land		-		-	1,500	
First-year operation		-		-	10,000	
Total costs					**278,026**	100.0%

The bold values is to emphasize important statements.

administrative overhead and/or to compensate unforeseen losses in fish or plant production.

3.4 | Model case

The main cost positions of the ModelCase were related to fish, plants, energy, water, labour, operation support, other costs and annuities (cf. material and methods). The contribution of the RAS and the HS to a particular position was expressed by the amount and the respective costs per unit of this contribution. The ModelCase caused annual costs of 278 k€ (cf. Table 5) and the main cost drivers were labour (41.5%), annuities (22.1%) and energy (10.8%).

For the production of fish fillet, a yield rate of 43% of the whole fish was assumed (Hoffman, Case y, & Prinsloo, 1993), and in Waren (DE), a consumer price of 19 €/kg (Fischkaufhaus.de, 2019) for fish fillet was obtained. For the ModelCase, the consumer price of the filleted fish was assessed with 20 €/kg (Mergenthaler & Lorleberg, 2016; Schröter, Hüppe, Lorleberg, & Mergenthaler, 2017) and that of the tomatoes with 4 €/kg. The benefits of the ModelCase were generated by direct sales of fish fillet (185 k€) and marketable tomatoes (168 k€) which resulted in a total of 353 k€. Processing and sales of fish and tomato residues are not considered here, but offer

TABLE 6 Annual benefits and the balance of the ModelCase

Benefits		kg	€/kg	€	Balance		€
RAS	Fish harvest	21,500					
	Filet ratio	43%				Benefits	352,900
	Fish sales	9,245	20	184,900		Costs	−278,026
	Slaughter waste	12,255			Results RAS + HS		**74,874**
HS	Tomato harvest	42,000					
	Not marketable	5%					
	Tomato sales	39,900	4	168,000			
	Tomato residues	2,100					
Total benefits				**352,900**			

The bold values is to emphasize important statements.

additionally economic potential. Considering the costs of 278 k€ the balance showed a profit of around 75 k€, indicating that the ModelCase would operate economically meaningful (cf. Table 6). Applying the same method as for ScenB, the hypothetical payback period would be around 7 years, significantly less than in ScenB.

4 | DISCUSSION

4.1 | Overall outcome

The Waren aquaponic facility harvested over 18.5 t fish and tomatoes together at the initial situation (InitS). With this result, it would belong to the upper 5% of aquaponic facilities sorted by production outcome considered in an international study (Love et al., 2015).

The inherent economic potential of the facility could not be fully exploited within InitS since the system did not reach its full working capacity during the starting phase. The main reasons were (a) the low productivity of both fish and plant production, (b) the inexperienced staff concerning the aquaponic technology and in particular the horticulture management and (c) the performed research which consumed additional efforts. As expected, InitS did not achieve profitability although a high tomato price could be achieved—due to a stable and regional market interested in regional and sustainable products. The operational loss was compensated by the facts (a) that the working power, needed to operate the facility, was partly funded by the above mentioned INAPRO project and (b) that the fish processing was done within the same company which could cross-subsidize the aquaponic facility. Furthermore, the investment was project-funded too; hence, no interest debited the calculation. Nevertheless, the loss of 2.74 € for the production of one kilogram tomatoes disclosed weaknesses. For example, an appropriate nutrient management is necessary to counteract nutrient imbalances in the transfer water and provide an optimum nutrient solution which is needed to maximize the yield and to prevent physiological plant disorders such as blossom end rot of tomatoes (Suhl et al., 2016). Conclusively after the adaptation phase to get experience and the professional skills needed for both units of the aquaponic system, the technological and economic performance of the Waren facility increased remarkably (cf. Figure 1).

The Scenario A (ScenA) demonstrated that a significant increase in productivity already led to a small margin from the operation of the facility without changing its size but exploiting the full productivity potential. In ScenA the RAS, operating on basis of an optimized production cyclogram could cover its running cost and even earn 6,789 €. The HS result was still negative with −2,701 €, although the tomato price remained at the high level of InitS. However, the loss of the HS was compensated by the electricity sale. ScenA would work for Waren because no interest had to be paid, but it would not be economically valid if the investment would be loan based.

An aquaponics designed for maximum utilization of the fish wastewater by the HS, as was the case with ScenB, leads to a harvest ratio of fish and vegetables production between 1:2 up and 1:5 depending inter alia on the fish species used (Kloas et al., 2015; Suhl, Dannehl, Baganz, Schmidt, & Kloas, 2018; Suhl et al., 2016). Due to the plant production winter break and the above-described limited transfer water utilization rate, the harvest ratio was about 1:2 in ScenB. However, the economy of ScenB was not so much improved by strengthening the aquaponic principle but rather by the increased production volume of the tomatoes and is therefore sensitive to the price of tomatoes.

The consumer price of tomatoes in Waren aligned within the high price segment between 3.0 and 5.5 €/kg due to (a) farmer-to-consumer direct selling of the food and (b) the special situation of Waren being a tourist centre and (c) the guaranteed exclusive freshness and ripeness of the products. Changes to the price at which the produced goods could be sold have a strong influence on the economic performance; thus, it will be quite sensitive to changes. For example: a more moderate tomato price of 1.5 €/kg instead of 3.5 €/kg in ScenB would drop the benefits about 90,000 € and in parallel turn the operational success of ScenB into failure. There was no information concerning the consumer price of fish because from the technical viewpoint of the PA for InitS, ScenA and ScenB, the fish was externally processed and sold to consumers.

The InitS was operated by an employee who had at the start little experience in the field of RAS, but none in the field of hydroponic tomato production. The involvement of an employee having experience in hydroponic cultivation of tomatoes would have a positive influence on productivity and had been assumed in ScenB (cf. Material and methods). Labour had a cost share in ScenB of one quarter (26%) in RAS but two third (66%) in HS, thus being by far the biggest cost share of the latter one. The influence of the increased HS size was reflected by the change of the cost structure. The relative share of HS energy costs was reduced from 28% (InitS) to 22% (ScenB) whereas the share of HS labour costs grew slightly from 61% to 66% but was related to a more than tripled HS productivity concomitant with more labour concerning cultivation and harvesting. With a margin of 16,624 € per year, ScenB was feasible and the hypothetical payback period remains below 12 years being less than the assumed operation life time of 15 years (cf. Table 4). ScenB proved that it is possible to operate such a rather small aquaponics even with a winter break as production scheme.

The economic outcome strongly depends on the market environment and the achievable prices which may differ remarkably under different local and regional conditions (Quagrainie, Flores, Kim, & McClain, 2018). Not comparable because of the absence of RAS, but noteworthy: For non-subsidized Spanish greenhouses (plastic tunnels as well as modern glass greenhouses), a dynamic payback period of 7–9 years was found (Dorogi & Apáti, 2019), but in the Almeria region, only 44% of the farms do not receive subsidies which enable them to survive (Valera, Belmonte, Molina-Aiz, & López, 2016).

This study does not investigate issues directly linked to the investment itself such as location, construction method, integration in existing buildings or technical equipment. A site resource inventory (a collection of building-specific and infrastructural parameters) can be helpful at this point for evaluating the suitability of a site for an aquaponic facility.

7.2 | Optimizing potential of Scenario B

Even if ScenB reveals profitability, it still has optimization potential regarding labour, prices, production scheme and others. Productivity is a key success factor and the FCR is of special importance for the RAS. Feeding, survival and growth data were recorded in studies (Hogendoorn 1983; Nguyen, 2016) and recalculated to FCR rates for 500 g fish (Bosma et al. 2017). If these data are extrapolated to 1.3 kg weight, an average FCR of 0.92 seems possible for African catfish. The main RAS cost driver in ScenB was fish feed (42%) and a reduction of the FCR by 15% would also reduce the amount of feed and cut the costs accordingly. Another key factor for the productivity of the system is the stocking density. African catfish can be reared at high stocking densities, which in turn could impair the consumer acceptance of aquaponics.

Pathogens at the RAS can lead to a total production failure; thus, disease prevention is crucial. The prevention of any disease at the HS is essential to avoid production losses which inevitably affect the productivity.

Concerning labour, an aquaponic facility runs 365 d per year, that means working force is required on weekends and holidays; furthermore, absences due to illness have to be taken into account. Even if one person would be sufficient to operate the facility for both the fish and the plant unit, a second operator with at least basic knowledge is needed to take over if necessary. In periods with a high workload, additional workforce will be necessary, employing, for example, seasonal workers or trainees. An important factor concerning the economic feasibility of aquaponics is the reduction of the HS labour costs for instance by automating, for example, nutrient supplementation and harvesting (Suprem, Mahalik, & Kim, 2013).

The current production scheme of ScenB involves a HS winter break, which bears further optimization Bosma et al. 2017) during winter times has to be introduced and this will, as a side effect, maximize the use of transfer water and nutrients. A functional modelling approach would be necessary to calculate the transfer water, the energy demand for greenhouse heating, CO_2 fertilization if applicable, and artificial light without a plant production winter break (Goddek & Körner, 2019; Körner, Andreassen, & Aaslyng, 2006).

7.3 | Adoption of the model case

The main economic figures comprised in the ModelCase fulfil two purposes: to be simple and complete. The figures described a most reasonable point within a bandwidth of possible values. When transferred to another use case, that is an adoption of the ModelCase to a planned project, the figures are to be customized because until now aquaponic facilities are not standardized and every facility is different concerning at least climate, location and market conditions.

The ModelCase cannot be directly compared with ScenB because of the changed boundary conditions. Nonetheless, there is the observation that the direct sales of the ModelCase led to a far better economic performance compared with ScenB, which relied on company internal prices. The annual profit of 75 k€ of the ModelCase outperformed ScenB, which earned around 17 k€ per annum.

The economic viability is the key success factor (Blay-Palmer & Donald 2006; Dürr, 2016) and its performance is sensitive against prices; thus, a small increase of the price for filleted fish would significantly affect the profitability of the facility. Fish processing (e.g. marinated or smoked products) would raise the profit of the facility too (FAO, 2019a, 2019b; Ward, 2003)—being already practised in Waren. Consideration should also be given to different fish species and the related consumer price. Even being already placed in the high price segment, there is the possibility that other tomato varieties like cherry tomatoes, coloured tomatoes, beef tomato or other varieties can get higher prices. The resulting necessary adaptations (e.g. stocking and planting densities, FCRs, nutrient requirements, growth rates) may afflict the whole balances of the aquaponic system and have to be considered in an adjusted model approach.

The herewith described aquaponics covers below 2,000 m^2 base area. In rural applications, it would be a mid-size facility and the economies of scale would offer optimizing potential because operating costs tend to decrease with an increasing size of a facility. The last decades demonstrated a trend that smaller greenhouses <1 hectare disappear and larger facilities of 2 to 10 hectares were opened in rural areas of the Netherlands, Spain and France (Buurma & Smit 2016; Velden & Smit, 2018). However, the ModelCase relies on direct selling but with a growing output this marketing channel will no longer absorb all goods—everything above a certain level has to be marketed at significantly lower prices via intermediaries and wholesalers. There is a high risk that these additional marketing channels will not allow cost-covering prices. This viewpoint is supported by the observation that there is a retail pricing structure maximum around 1,000-m^2 plant-growing area (Lennard, 2017).

7.4 | Urban application

Appropriate application fields for professional aquaponics of the ModelCase size are urban and peri-urban areas with their limited space availability and competition of different usage types. Aquaponics has its place already within urban agriculture but professional facilities are rather rare (Proksch, 2016). When scaling up the number of aquaponics from the contemporary very few to a significant number, the economic viability of medium size aquaponic facilities would get under pressure. Direct selling, for example, will be limited for the whole output of all facilities within a given urban context. Of course, an individual urban aquaponics can find the optimum size depending on the location and it can significantly improve its performance by diversification: unique marketing stories, agro-tourism activities, educational opportunities, events and gastronomy, but above a certain number of farms forms of cooperation and the usage of the peri-urban space are options to be considered.

Multi-loop aquaponics with its inherent circles fits well into the concepts of circular economy and local food production (Stadler, Baganz, Vermeulen, & Keesman, 2017). A site with access, for example, to waste heat could be used to reduce energy costs significantly. If waste heat sources of higher temperatures > 80°C or sufficient solar radiation are available, even effective cooling can be achieved in summer and energy costs are reduced further (Ghafoor & Munir, 2015; Nour, Ghanem, Buchholz, & Nassar, 2015). The ability of aquaponics to minimize the wastewater of a fish production system to near zero is a clear advantage over other animal protein production methods (poultry, pork, cattle) which have water footprints being twofold to sixfold higher than RAS fish production (Mekonnen & Hoekstra, 2012; Zimmer & Renault, 2003). In a future smart city, all different agents along the way from the producer up to the consumer, together with scale effect inherent to different kinds of aquaponics explorations are to be regarded (dos Santos, 2016). In urban areas, the possibility exists to use common aquaponic infrastructure synergistically. This may start with a slaughter- and salesroom which might serve for more than one facility and it can end up with a spatial separation of the two main loops of a DRAPS. For instance one building integrated RAS is able to transfer water to several different rooftop HS or for producing vertical green. Aquaponics could be a mean to bring sustainable food production into the city and can become part of a resource-efficient urban agriculture (Proksch, Ianchenko, & Kotzen, 2019; dos Santos, 2016), where especially differentiation and diversification are key factors for an economic viable development (Pölling et al., 2017). Urban gardening including aquaculture is already more and more legally defined and permitted in different states of the United States (Chicago, 2020; CLC_Baltimore, 2015; USDA, 2016) whereas in the EU recently only intentional statements or suggestions for legal instruments from policy can be found (EPRS, 2017; Piorr, Zasada, Doernberg, Zoll, & Ramme, 2018).

8 | CONCLUSION

Two scenarios (ScenA, ScenB) were developed on the basis of the ex post PA of an aquaponic facility in Waren (DE) as intermediate steps to find an economically profitable solution for a comprehensive aquaponics model case (ModelCase). ScenA covered the operation costs of the facility and made a small profit but failed to pay back the investment whereas the aquaponic configuration of ScenB was profitable. The ModelCase extended ScenB comprising a complete set of the main economic figures which values have to be specified for any adoption to another location. In this case study, the ModelCase is economically viable under the conditions of funded credits, direct sales and without major production outages. It has been shown that it is possible to combine sustainability and profitability by means of multi-loop aquaponics. This efficient food production solution can be feasible if it exploits its potential, regardless of the high initial investment costs and by considering the following aspects:

- Investment: the location and the way the facility is implemented determine the success of the project from the outset and an appropriate operating model is needed.
- Market environment: market capacity, prices, consumer behaviour and aquaponics image require serious analysis to develop a suitable distribution model. The output of the facility should not exceed the demand and constant supply to the market as well as constant purchase of the produced goods by the consumers is of importance.
- Diversification: economic activities beyond the core business can significantly improve the earnings situation.
- Knowledge: skills and experiences in fish and plant production techniques are necessary. In general, professional staff is indispensable for both production units in a commercial facility.
- Optimization: due to its direct impact on economic success, high productivity should be aspired (e.g. densities, growth rates, FCR), including the avoidance of risks for fish and plants due to mismanagement.
- Cost reduction: labour and energy are the main drivers of the operation costs and a reduction should be considered, for example, through automation and the use of alternative energy sources.
- Endurance: the ModelCase needs around 7 years to reach the break-even point based on direct sales whereas the enterprise

internal prices of ScenB could be interpreted as another distribution model (wholesale) which leads to break-even in 12 years.

The medium-sized ModelCase does not fit well in a rural context, where larger facilities are advantageous due to the economies of scale. However, this facility size may of importance in the urban area, as there is much higher competitive pressure in terms of area and location. In times of increasing urbanization, further research is needed to better specify the requirements and benefits of professional aquaponics under urban conditions, in order to contribute to the nutrition of people in cities. A change in territorial strategies, policies and landscape planning instruments would be essential (Lohrberg, Licka, Scazzosi, & Timpe, 2015) as the influence of urban planning and policy is important regarding aquaponics in an urban context (Pollard, Ward, & Koth, 2017).

ETHICS STATEMENT

Ethics Statement: The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. No ethical approval was required.

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DATA AVAILABILITY STATEMENT

The data used in the paper will be available in Excel format at the IGB-Repository (FRED) on publication https://doi.org/10.18728/531.1. No further supporting data are available.

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