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REVIEW

REVIEWS IN Aquaculture

The aquaponic principle — It is all about coupling

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Abstract

The aquaponic principle is the coupling of animal aquaculture (e.g. fish) with plant production (e.g. vegetables) for saving resources. At present, various definitions of aquaponics exist, some bearing the risk of misinterpretation by dismissing the original meaning or being contradictory. In addition, there is no standard terminology for the aspects of coupling between the aquaponic subsystems. In this study, we addressed both issues. (1) We developed new or revised definitions that are summarised by: Aquaponic farming comprises aquaponics (which couples tank-based animal aquaculture with hydroponics) and trans-aquaponics, which extends aquaponics to tankless aquaculture as well as non-hydroponics plant cultivation methods. Within our conceptual system, the term aquaponics corresponds to the definitions of FAO and EU. (2) A system analysis approach was utilised to explore different aquaponic setups aiming to better describe the way aquaponic subsystems are connected. We introduced the new terms 'coupling type' and 'coupling degree', where the former qualitatively characterises the water-mediated connections of aquaponic subsystems. A system with on-demand nutrient water supply for the independent operating plant cultivation is an 'on-demand coupled system' and we propose to deprecate the counterintuitive term 'decoupled system' for this coupling type. The coupling degree comprises a set of parameters to quantitatively determine the coupling's efficiency of internal streams, for example, water and nutrients. This new framework forms a basis for improved communication, provides a uniform metric for comparing aquaponic facilities, and offers criteria for facility optimisation. In future system descriptions, it will simplify evaluation of the coupling's contribution to sustainability of aquaponics.

KEYWORDS
aquaponic farming, aquaponics, coupling degree, coupling type, permanently/on-demand coupled, trans-aquaponics

1 | INTRODUCTION

Aquaponics is a portmanteau of aquaculture (the farming of aquatic organisms) and hydroponics (the soilless cultivation of plants) that refers to a technology coupling both in one system where the nutrient-rich water from aquaculture is used as fertiliser for the cultivated plants.[1] Microorganisms, especially bacteria, are the third key component due to their functions in nutrient transformation.[1-4]

The circular nature of aquaponics is emphasised by, for example, Naegel[5] and Rakocy et al[1] and various studies showed the efficiency of this coupling approach.[6-11] The two main aquaponic units, aquaculture and hydroponics, have been independently developed and optimised over the past decades. If aquaponics is expected to be commercially successful,[12-14] both units have to operate at the, respectively, achieved state of the art. The first iterations of the aquaponic concept appeared in the 1970s and 80s without the use of the term 'aquaponics' but instead referring to the concept as, inter alia, 'combined fish and vegetable production in greenhouses' or 'combined production of fish and plants in recirculating water'.[5,15,16,17] However, since the start of publication of the Aquaponics Journal in 1997[1] the term aquaponics was generally used, despite other terms remaining in use such as 'integrated fish/vegetable co-culture system'.[18]

Aquaponics received increasing popularity during the last two decades. However, a current analysis of *Google trends* for 'aquaponics' (Figure 1) suggests that aquaponics may have reached the level of disillusionment according to *Gartner's hype cycle*.[19] Yet, the occurrence of aquaponics from 1990 to 2019 in the *Google corpus of books* (Figure 1) shows a mostly unbroken upward trend. The increasing usage of the term 'aquaponics' in books can be taken as an indicator for the continued interest in the technology, even if Googles Ngram viewer may have weaknesses.[20]

Aquaculture reached 46% of the global fish production in 2018.[21] It provides the only possible solution for meeting increased market demand[22] and contributes to transforming food systems for affordable healthy diets,[23] but it is not coming without negative environmental aspects.[24] In aquaponics, the aquaculture effluent is diverted through plant beds and not released to the environment, while at the same time the nutrients for the plants are supplied from a sustainable, cost-effective and non-chemical source.[25] Thus this integration removes some of the unsustainable factors of running aquaculture and hydroponics systems independently.[25] Moreover, aquaponics contributes to food security[26] and food sovereignty.[27] Applied locally within community-supported agriculture, it can also play a role in food assistance, in line with the respective UN convention.[28] Gaps for economically successful applications are identified and can be closed.[29]

At present, different definitions of 'aquaponics' exist: some authors restrict the plant cultivation of aquaponics to hydroponics[10,30] while others are in favour of expanding the term and detaching it from its original meaning.[31] First aquaponic systems, for example, the *University of the Virgin Islands approach*[32] consisted of one recirculating loop and were, later on, referred to as *coupled systems*[33] or *single recirculation aquaponic* systems.[10] Later developed aquaponics with a physical separation into aquaculture and hydroponic loop was called *decoupled aquaponic systems*[34] or designated as *double recirculation aquaponic* systems.[10] We would like to note that the term decoupled is counterintuitive in aquaponics because it is used to classify a system whose very nature lies in the coupling of two subsystems. For that reason, the dichotomy of coupled/decoupled systems is subject to discussion in this study. A further challenge regarding concise definitions is to identify and compare the effectiveness of the coupling of aquaponic units from the literature, equally whether it pertains to models or actual facilities. For example, Baganz et al[12] offer extensive production data from a commercial plant but give only a little information on the coupling efficiency between aquaculture and plant cultivation. Consistent and unambiguous terminology is essential and urgently required to facilitate communication not only among aquaponic professionals and new entrants into the field but also among the broader stakeholder base involved in the realisation of future projects. This includes public authorities, planners, architects, researchers and practitioners as well as the broader interested public aiming to integrate aquaponics into urban, peri-urban and rural landscapes; valorising aquaponics as a rising nature-based solution within circular economy loops.

The objectives of this study are, therefore: (1) to discuss existing aquaponic definitions, (2) to provide a new definition set encompassing all aquaponic approaches, (3) to develop a framework through a system analysis approach to assess coupling aspects of aquaponic units, and (4) to challenge a few aquaponic terms currently in use and introduce intuitive new ones. The purpose of this undertaking is to provide improved

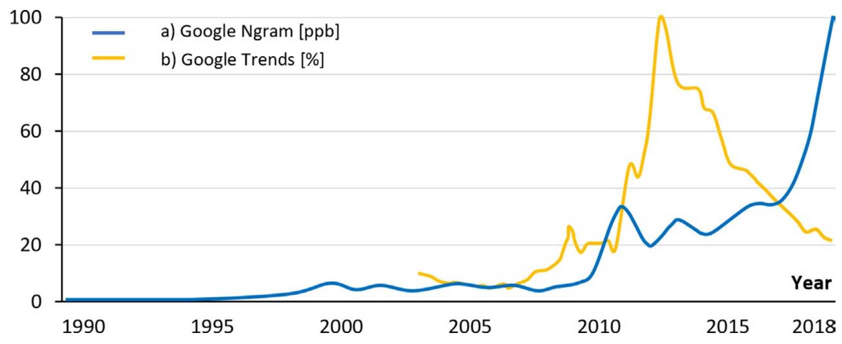

FIGURE 1 Occurrence of the unigram 'aquaponics' over time (a) in Googles Ngram viewer as ppb of the Google corpus of books (authors work) and (b) in Google trends as a per cent of maximum[19]

descriptions of domain-specific real-world phenomena regarding aquaponics as well as a metric to better compare aquaponic systems.

2 | AQUAPONICS, TRANS-AQUAPONICS AND AQUAPONIC FARMING

Using resources from aquaculture for plant cultivation forms the aquaponic principle. All technologies adhering to this principle possess at least two subsystems, often in separated units, but discussing their definition is beyond the scope of this study. Most authors agree that aquaculture is the rearing of aquatic organisms under controlled or semi-controlled conditions[35-39] and hydroponics is a soilless plant cultivation method in which all nutrients are supplied to the plant via the irrigation water.[40-42] It should be noted that aquaculture includes aquatic animals (e.g. fish, mussels and crustaceans) as well as plants (e.g. micro- and macroalgae).[39] When integrated into aquaponics, aquaculture is restricted to aquatic animals because only the heterotrophic animal metabolism is creating emissions usable as a nutrient base for autotrophic plants. Emissions from (marine) cage-farming aquaculture can be used within *integrated multi-trophic aquaculture*,[43,44] whereas those from land-based aquaculture are utilisable within aquaponics.

The term ‘aquaponics’ is defined quite differently, as two recent examples show. Lennard[30] states that aquaponics is (1) ‘A system of integrating tank-based fish culture and hydroponic plant culture whereby 80% or more of the nutrients required to grow the plants arise from the fish waste.’, whereas Palm et al[31] declare (2) ‘Aquaponics is a production system of aquatic organisms and plants where the majority (>50%) of nutrients sustaining the optimal plant growth derives from waste originating from feeding the aquatic organisms.'. A comparison of these definitions raises the issues of: (1) whether aquaponics is necessarily fish tank-based; (2) whether the levels of the nutrient thresholds are already established; (3) which elements ought to be considered in an aquaponics’ definition; and (4) whether the term aquaponics can be applied to all relevant coupled aquaculture and plant cultivation methods.

Concerning the first definition issue, Rakocy et al[1] pointed out that multiple tanks enable sequential rearing and the resulting staggered fish production (cf. Section 3) leads to a more regular nutrient supply for the plants. The restriction to tanks is omitted by Wirza and Nazir[45] referring to Rakocy et al[1] in their aquaponics’ description. Lennard[30] does not justify restricting his definition to fish tanks but points out the frequent use of recirculation aquaculture systems, which require fish tanks. However, fish tanks as part of aquaponics seem to be a general consensus included in a recent educational textbook by Junge et al.[46]

The second definition issue is related to the minimum share of nutrients that plant cultivation should receive from aquaculture, which is given as ≥80% by Lennard[30] or >50% by Palm et al.[31] The nutrients threshold is intended to ensure the benefit of the aquaponic coupling but is, however, problematic: (1) considering the dual use of water in aquaponics, there should also be a water re-usage threshold; (2) the range of values quoted above indicates the problem of threshold determination and a formulation such as ‘considerable amount’ would not correspond to the precision expected from a definition; (3) it is questionable whether all systems excluded by a threshold are indeed not aquaponics; (4) whether the threshold applies for a single nutrient optimum (e.g. N or P) or the cumulative mass of all nutrients remains open; (5) it has to be considered that each plant species requires a specific optimal range for each nutrient and that the aquaculture effluent does not provide these macro- and micronutrients in sufficient quantities and/or required nutrient ratios for optimal growth.[47,48] Moreover, most nutrients are currently difficult or impossible to monitor continuously. We, therefore, prefer to omit the nutrient threshold as an element of definition and leave it to the processes of legal classifications or the specifications of quality labels. We will later introduce the nutrient coupling degree and justify the rejection of thresholds in more detail (cf. section ‘Coupling degree—quantitative aspects of the aquaponic unit coupling’).

The third definition issue is whether (and which) other elements besides thresholds are part of the definition. (1) Microorganisms should be included[45] as these are critical to the success of any aquaponic setup.[2,4,49,50,51] Additional beneficial microorganisms can further enhance the performance of some fish when applied in biofloc technology,[52,53] which is used in aquaponics as well.[54,55] (2) The aquatic taxa are not restricted (e.g. to fish) as long as they fit appropriate zootechnical characteristics and provide nutrients for plant cultivation. (3) Since the use of metabolic emissions is inherent to the aquaponic principle, the term ‘waste’ (e.g. fish waste) might be misleading in this context and is omitted. Waste should only be used for nutrient/emission streams that exit the aquaponics entirely. (4) Aquaponics is mostly thought to be just a food production technology, but as part of the definition, this aspect would exclude, for example, ornamental fish, as well as medicinal herbs. (5) Water is a definition element, not only because water is the meaning of both aqua (Latin) and hydro (Greek, hýdor), but especially since aquaculture and hydroponics are coupled by the multifunctional use of water (a) to transfer aquatic animals’ metabolic emissions as nutrients from aquaculture to plant cultivation and (b) to irrigate the plants with the nutrient water (fertigation). This also applies if the respective organisms are not spatially separated or the nutrient water is stationary, as is the case with the ancient Aztec Chinampas.[56,57] Without ‘water’, an aquaponic definition would include cases where aquaculture and hydroponics are far apart and nutrients are transported by other means, such as in a dry state. Aquaculture waste would be a resource, for inter alia plant cultivation or as food for amphipods,[58] but the principle of direct coupling would be abolished. (6) The maximal spatial separation of the aquaponic units covered by definition remains open, but we restrict the transport medium to water which limits the practical distances somewhat. Based on these deliberations we propose the following definition of aquaponics:

> Aquaponics is a technology that couples tank-based animal aquaculture with hydroponics—involving microbiological processes - using water from aquaculture for plant nutrition and irrigation.

The fourth definition issue concerns the extension of the term aquaponics to other aquaculture and plant cultivation methods. FAO[25,39] states that hydroponics is a prerequisite for aquaponics, while Palm et al[31] define no restrictions regarding the aquaculture or plant cultivation technology and distinguish both taxa by the additions *sensu stricto* (s.s.) and *sensu lato* (s.l.) to designate aquaponics in the 'narrower sense' or 'broader sense'. These additions create complications: (1) The aquaponic definition of Palm et al[31] is not backwards compatible since its meaning of 'aquaponics' (functioning as an overarching term) comprises 'aquaponics s.l.', which was intentionally excluded from the original definitions.[1,30] (2) Hence, if aquaponics in the narrower sense is used without 's.s.', there is a risk of confusion with the term 'aquaponics' one taxonomy level higher. (3) It remains unclear whether 'aquaponics s.l.' is synonymous with 'aquaponics'; in this case the discrete set disjoint to 's.s.' would be missing. (4) Neither of the additions is part of the definition, but merely contained in the associated explanations.

Production methods that do not use tank aquaculture or hydroponics have also been referred to as aquaponics, for example, pond-aquaponics,[59,60] outdoor aquaponics,[25,61] aqua-terra-ponics,[62] aquaculture sludge removal by constructed wetland,[63] and other technologies.[64,65] Like aquaponics, they exploit the aquaponic principle but often rely on soil, a boundary-determining criterion[66] justifying the formation of a separate taxon. We propose 'trans-aquaponics' to refer to *integrated aqua-agriculture systems*,[67] which follow the aquaponic principle but are disjoint from aquaponics; thus 'aquaponics' retains its original meaning. Besides the above-mentioned methods, even rice-fish[61,68,69] belong to the trans-aquaponic taxon, but livestock-fish co-cultures[70] are excluded.

> Trans-aquaponics couples aquaculture with plant culture by extending aquaponics to tankless aquaculture as well as non-hydroponics plant cultivation methods.

Aquaponics was proposed as a term overarching the 's.s.' and 's.l.' taxa, even if called into question: 'The suffix "ponics" in hydroponics, as well as aquaponics, comes from the Greek "ponos" for work, and thus, the term aquaponics is unfortunate as it really translates as "waterwork" which does not adequately describe what the system really is and what it does.'[31] This problem does not exist with our revised definition, because aquaponics remains a portmanteau of aquaculture and hydroponics. We propose 'aquaponic farming' used inter alia by FAO[25] as an umbrella term for all technologies exploiting the aquaponic principle, independent of facility size:

> Aquaponic farming comprises aquaponics, as well as trans-aquaponics.

The three definitions are formally summarised as: 'Aquaponic farming comprises aquaponics (which couples tank-based animal aquaculture with hydroponics) and trans-aquaponics, which extends aquaponics to tankless aquaculture as well as non-hydroponics plant cultivation methods'. A more explanatory summary for a broader audience is: 'Aquaponic farming comprises aquaponics (which couples tank-based animal aquaculture with hydroponics), as well as trans-aquaponics, which includes *integrated aqua-agriculture systems* exploiting the aquaponic principle without these restrictions'. The dependencies of the definitions are visualised in Figure 2. The terms 'aquaponic farming' and 'trans-aquaponics' indicate the underlying aquaponic principle, even if these taxa partially or completely exclude 'aquaponics'.

The importance of clear definitions can be seen, for example, in the discussion of whether aquaponics can be eco-certified. Aquaponics is not included in the EU organic agriculture certification scheme because it exploits hydroponics.[71] However, a trans-aquaponic application coupling organic aquaculture[72] with soil-based organic food production[73,74] could be certified as 'organic'.

3 | SYSTEM ANALYSIS OF AQUAPONIC UNIT COUPLING

The following brief system analysis is limited to (fish-based) aquaponics to avoid considering special cases of trans-aquaponics, but

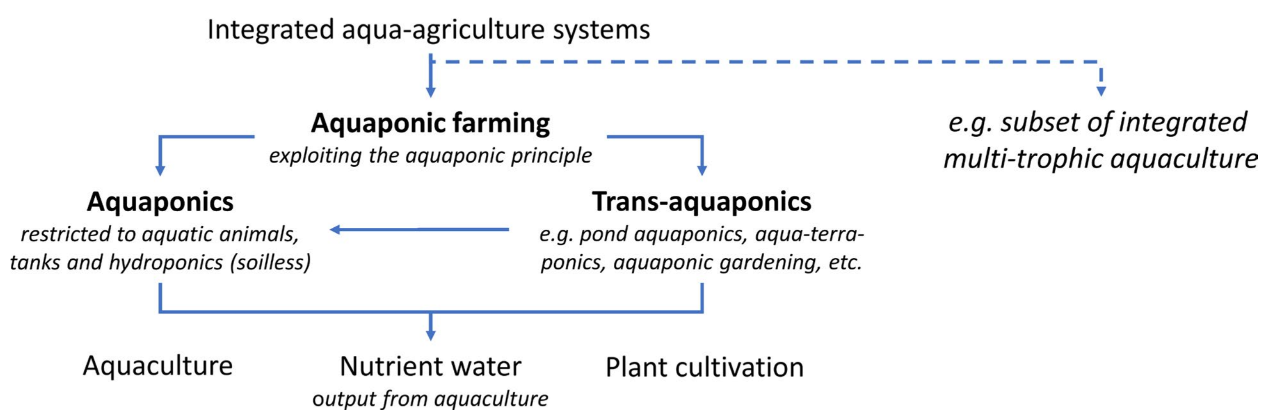

FIGURE 2 Definition dependencies, the arrow direction indicates access to required definitions

can in principle also be applied to it. To carry out a complete evaluation of the environmental footprint of aquaponics, a life cycle assessment is required[75] in which the system boundaries proceed along all processes involved. A simplified view is to consider an aquaponic system as a black box with a system boundary defined by its input and output streams.[76] These material flows can be used to determine the overall effectiveness of an aquaponic facility. One measure of the overall performance of an aquaponic facility concerning water consumption is the daily need for freshwater in relation to biomass output; hence we introduce the *facility product water use*.

> The Facility Product Water Use is the average water volume needed by a specific facility to produce one kg of fresh product within one year.

Because aquaponics has multiple product outputs, at least fish and plants, the internal streams must be attributed for in the calculation. Our definition separates the *facility product water use* from the water footprint, which adds the water consumption resulting from all product-related processes, mostly not under the owner's control. In contrast, the owner can exert influence on the *facility product water use* by altering production schemes.

4 | CONCERNING SOME AQUAPONIC TERMS

As with any technical language, aquaponics has definitions that are domain-specific and sometimes not very precise. For example, bioreactor and its subcategory 'moving bed bioreactor'[77] which provide the habitat for nitrifying bacteria are often called biofilter in aquaponic context, even though nothing is filtered out here. Rather than that, chemical compounds are altered and bacterial biomass is built up—the transformation of fish-toxic ammonia and ammonium over nitrite to nitrate by nitrifying bacteria.[12] Besides this, there are different terms used for the water transferred from the aquaculture to the plant cultivation, the most important internal stream of matter in aquaponics, which is called fish water,[78] fish wastewater,[79] process water,[80] RAS water (RAS = recirculation aquaculture system)[81] or transfer-water.[10] Concerning the use of terms in this article, we (1) prefer 'facility' over 'plant' to avoid confusion related to the term plant (vegetable) and (2) 'unit' (or subsystem) over 'compartment' for conciseness, reserving 'component' for the unit's elements, which then can be described, for example, by component diagrams of the *Unified Modelling Language*. (3) In aquaponic contexts we discourage 'symbiosis' and propose 'synergy' which means 'working together'. Symbiosis is related to co-evolution,[82] and therefore, the aquaponic based relationship between organisms is not symbiosis, regardless of methods such as 'symbioponics' coined by Lennard.[83] (4) For the water transferring nutrients from aquaculture to hydroponics, the term 'nutrient water' is preferred over the other variants mentioned above since this term indicates its purpose by its name. (5) Process water, as a broader term can be applied in other situations.

5 | COUPLING TYPES – QUALITATIVE ASPECTS OF THE AQUAPONIC UNIT COUPLING

When assessing aquaponic unit coupling, the focus lies on the internal streams. Thus, a white-box approach is used for the whole system with aquaculture and plant cultivation remaining black boxes except for the local assignment of the majority of nitrifying bacteria. We propose the term coupling type to describe the qualitative aspects of streams that can flow between the aquaponic units, for example, water, nutrients, heat, O_2 and CO_2, whereby the water relation describes the general coupling scheme. As dissolved nutrients are transported in water, both streams are closely connected. Aquaponic systems can be roughly divided into two water/nutrient-related coupling types, which are mutually exclusive:

1. permanently coupled: permanent coupling with tightly coupled units ('coupled' system)
2. on-demand coupled: on-demand coupling with loosely coupled units ('decoupled' system)

The terms permanently and on-demand are not only a temporal distinction but describe the respective inherent structural possibilities of aquaponic unit coupling. In an aquaponic farm with more than one set of aquaponic units operating independently in parallel, such as in experimental settings, the set units can be coupled permanently or on-demand.

The permanently coupled type of aquaponic systems features one water loop from aquaculture to hydroponics and back to aquaculture. In its classical form, without biofilter, the nitrification of aquaculture effluents takes place in the hydroponics[84] with its high proportion of *specific surface area* for the formation of bacterial colonies. With insufficient *specific surface area*, an additional settler or a biofilter can be installed upstream. Significantly more water goes to the hydroponics than the plants need; otherwise not enough filtered water would flow back into the aquaculture unit. Both units are permanently coupled; they are interdependent and cannot be operated separately (cf. Figure 3).

Permanently coupled aquaponics consists of one single main loop on the overall aquaponic level, but features optionally sub-loops or bypasses on the aquaculture side to allow adjusted water flows via aeration units and/or mechanical filtering. In case of winter break in plant production, additional hydroponics, for example, with *Lemna minor* L. can be installed as biofilter.[62,85] However, as long as the main recirculation flow passes through the hydroponic unit and then directly back to the aquaculture unit, both are permanently coupled. This type comes with limitations due to the different water quality requirements of fish, bacteria and plants, which have different optima, for example, in respect to the pH

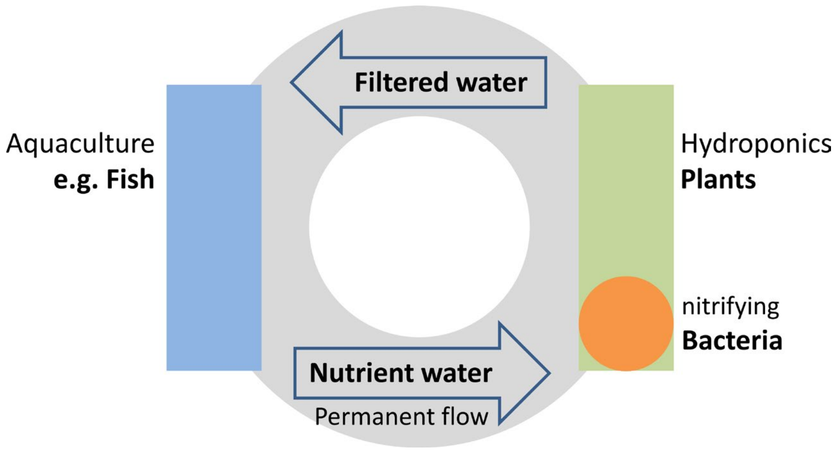

FIGURE 3 Permanently coupled aquaponic units (blue, green), a mandatory two-way connection forms one loop (grey), classical approach without a biofilter

value.[86] Another issue is the plants' nutrient requirements, which cannot be fully covered by the nutrient water.[78,87] Regarding synergy in aquaponics,[88] the synergistic effects form a cycle: fish > bacteria > plants > fish.

To overcome the restrictions resulting from coupling the aquaponic units permanently, separate water circulations were introduced for the aquaculture and hydroponic units respectively.[10] In this setup, the flow of nutrient water is based on the requirements of the hydroponic unit and hence we call it 'on-demand coupling'. With on-demand coupling, hydroponics loses the biological treatment function essential to the aquaculture unit, which thus needs to be a *recirculating aquaculture system* with an integrated biofilter. It follows, that the aquaponic units may be separated without harming either aquaculture or hydroponics and that both can also operate independently from each other. Optionally, the evaporated water in the hydroponics (greenhouse) can be regained via cooling/condensation traps as condensate[89] or desalination/distillation technologies (e.g. reverse osmosis)[90] and returned to the aquaculture unit to minimise the overall water consumption of the system (cf. Figure 4). The result is a multiple-loop system,[75,91] which means that a remineralisation unit, a concentration unit or other units may add further loops.

The key advantage of on-demand coupling is that optimal conditions can be achieved separately in each aquaponic unit, for example, parameters setting the detoxifying fish > bacteria > fish conditions within the aquaculture. The on-demand coupling synergy is first of all unidirectional because fish have no advantage from plants: fish > bacteria > plants. A two-way connected setup changes the synergic topology to circular: fish > bacteria > plants: regained water > fish. With an additional exchange of gases, a direct synergy between fish and plants is possible: fish: CO_2 > plants: O_2 > fish.

The coupling type of aquaponic units has various attributes (cf. Table 1): nutrient water flow, the primary location of the presence of nitrifying bacteria, synergy topology, independent operation of both aquaponic units, required aquaculture cycle, one- or two-way connection, etc.

6 | COUPLING DEGREE—QUANTITATIVE ASPECTS OF THE AQUAPONIC UNIT COUPLING

The coupling type is about the setup and qualities of the aquaponic unit coupling but has no information on quantities. We propose coupling degrees encompassing a set of parameters that collectively represent the criteria for objectively evaluating a facility's coupling effectiveness and sustainability. This set includes water, nutrients, energy (e.g. heat), coupling time (e.g. considering a break in the plant production) and other parameters over a given measuring period, for which we propose at least one year for better comparability. To describe the overall coupling, the coupling degrees of water and nutrients (e.g. N, P and K) are essential, because in aquaponics, a balance is sought between the two production units in a way that maximises nutrient use while concomitantly minimising *facility product water use* by reducing wastewater.

We developed a general form of direction-sensitive coupling degrees, as shown in formula [1] and [2], using the camel case naming convention.[92] Each coupling degree refers to one parameter of the set and is expressed with respect to the stream direction (in, out) and the parameter as follows:

$$\text{CouplingDegreeOut}_{\text{param}} = \text{StreamTo}_{\text{AP unit, param}} / \text{TotalOutputFrom}_{\text{AP unit, param}} \tag{1}$$

$$\text{CouplingDegreeIn}_{\text{param}} = \text{StreamFrom}_{\text{AP unit, param}} / \text{NeededInputTo}_{\text{AP unit, param}}. \tag{2}$$

Whether the coupling degree refers to an input or an output relationship should be indicated by the naming conventions, for example, terms such as 'out', 'provided' and 'delivered' refer to the output whereas 'in', 'required' or 'need' concern the input. An application of formula [1] is: let AcOutputWater be the water output (including sludge water fraction and filter rinsing) from aquaculture and TransferWater be the water flow from aquaculture to hydroponics,

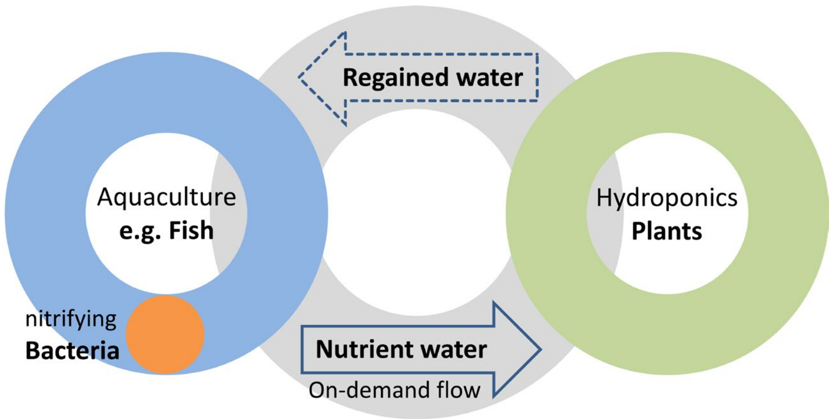

FIGURE 4 On-demand coupled aquaponic units (blue, green), one-way connected, an optional second connection forms a loop at the aquaponics' level (grey)

TABLE 1 Comparing attributes of permanent and on-demand water-related aquaponic units coupling

	Water coupling type	
Coupling attribute	Permanent	On-demand
One-way connection	N/A	Mandatory
Nutrient water flow from aquaculture to hydroponics	Continuous	Discontinuous, continuous
Two-way connection	Mandatory	Optional
Reflux from hydroponics to aquaculture	Continuous	None, discontinuous (intermittent), or continuous
Independent operation of both aquaponic units	No	Yes
Aquaculture cycle with biofilter	Optional	Mandatory
Synergy topology	Circular	Unidirectional, optional circuit closure

Note: Two mutually exclusive attributes describe the physical water connections of aquaponics: (1) with only a unidirectional connection from aquaculture to hydroponics, both units are one-way connected; (2) adding a second unidirectional connection from hydroponics to aquaculture makes them two-way connected. Permanently coupled aquaponics is always two-way connected, while in an on-demand coupled system the second connection from hydroponics to aquaculture is optional. Concerning the plant supply, both water and nutrients flow in only one direction. Due to this fact, 'nutrient water' comprises only the water flow from the aquaculture to the hydroponics, even in two-way connected aquaponics. In this case, the reflux of water is optional (cf. Table 1).

then the water-related coupling degree of aquaponics is calculated as follows:

$$\text{CouplingDegreeWater} = \text{TransferWater}/\text{AcOutputWater}. \quad (3)$$

The water coupling degree can be used as a criterion to size aquaponic units: 'As in a closed-loop system the main water use is due to plant transpiration, the necessary sizes of system and subsystem depend on plant transpiration'.[81]

Another criterion for the size of aquaponics are the nutrients[83] and these are determined by the composition and amount of fish feed, which depend inter alia on the species of fish being farmed. Generally, sturdy fish species which can be reared at higher densities and tolerate elevated levels of suspended solids and dissolved nutrients, are ideal candidates for aquaponic production.[1,93] In practice, various tilapia, carp and catfish species are the most common species of choice.[94,95] However, many other species such as rainbow trout (*Oncorhynchus mykiss*), largemouth bass (*Micropterus salmoides*), tambaqui (*Colossoma macropomum*) or barramundi (*Lates calcarifer*) are potentially suitable.[1,93,96] Even brackish or saltwater species and crustaceans in combination with complementary plant species may present opportunities to widen the scope of aquaponic production.[97,98]

Microbially converted metabolic emissions from fish and 'uneaten feed and organisms (e.g. bacteria, fungi and algae) that grow in the system'[1] play an important role as a nutrient source for plants in the coupling of both units. Equation (2) refers to the coupling degree of incoming streams. Applied to hydroponics, let HpNutrientsNeeded be the amount of nutrients needed for optimum production in hydroponics and let NutrientsTransfer be the mass of all dissolved nutrients in the nutrient water, then the hydroponics nutrient input coupling degree is:

$$\text{CouplingDegreeNutrientsIn} = \text{NutrientsTransfer}/\text{HpNutrientsNeeded}. \quad (4)$$

Suhl et al[78] reported for tomato production in aquaponics that the maximum fertiliser reduction was 77.7% compared to standalone hydroponics. For lettuce production, the total fertiliser requirement could be reduced by 62.8% using nutrient water to mix the nutrient solution for lettuce.[87] The ratio of nutrients in the nutrient water depends on the individual set up of the aquaculture unit (species, stocking density, feeding ratio, environmental water parameters etc.) and does not correspond to the optimal ratio required for the plants, for example, in one experiment 128% N but only 17% P and 17% K of the optimal plant supply were measured in the nutrient water.[10]

A solution here might be to use the concepts 'fertiliser use efficiency'[99] or 'nutrient use efficiency'.[90] *CouplingDegreeNutrientsIn* can be different for every essential element[48,100] and there is a conflict of objectives in whether N or P should be used to optimise the dimensioning of aquaponic subsystems.[46,81]

The *CouplingDegreeNutrientsIn* is determined from the hydroponics' perspective. Thus, this value refers to the nutrient water while the nutrients leaving the aquaculture unit as waste are not considered. The nutrient aquaculture output coupling degree is more informative with regard to the aquaponics internal nutrient utilisation:

$$\text{CouplingDegreeNutrientsOut} = \text{NutrientsTransfer} / \text{AcOutputNutrients}. \quad (5)$$

The nutrient threshold given in the above definition examples (cf. Section 2) refers to *CouplingDegreeNutrientsIn*. However, even if it covers a considerable amount of the plant's demand, *CouplingDegreeNutrientsOut* can perform on a significantly lower level. To express the efficiency of the aquaponic nutrient coupling, *CouplingDegreeNutrientsOut* would have to be used, which can be improved, among other things, through sludge remineralisation.

There are specific requirements that require other coupling metrics, and the degree of coupling must be known in each case. (1) The relation between fish feed and hydroponic area, for example, the *University of the Virgin Island's feeding ratio* suggest 60–100 g fish feed per m² hydroponics and day based on a deep flow approach.[30,84] Albeit, the quality of the diets is related to the nutritional requirement of each fish species and their developmental stages.[96] Therefore, the amount of nitrogen input will be different. (2) Another coupling metric is the fish/plant harvest ratio. The latter is a limited way to compare facilities as it cannot be used without restrictions due to its aggregated form. The fish/plant harvest ratio depends, among other things, on the aquaponics' configuration, types of fish and plants, mode of operation, productivity, etc. Other dependencies between both units are inter-alia, (3) that the hydroponics is driven by light and the size of aquaculture in a balanced aquaponics consequently follows this parameter as form follows functions,[101] and (4) that plants are nourished indirectly by fish feed, which therefore, must not contain substances in quantities that are harmful to plants.

The coupling of fish and plant production seems simple at first glance but becomes more complex upon closer inspection. There are many possible configurations of an aquaponic system, depending on climate zone, market conditions, the combination of species cultivated, and the specific location, among other factors.[102] When designing such a system, it is crucial to determine the relationship between the dimension of both aquaponic units, or in other words, how to optimally couple them, and this is where models can be helpful,[81,103] preferably when validated with real-world data.

Baganz et al[12] described commercial aquaponics in Germany, and a view on actual production data (cf. Figure 5) reveals (1) that staggered fish production starts about one batch per month to produce a relatively constant nutrient/water output and (2) that the dates for fish sales, determined by growth rate and market demand, are not regular. These irregularities may occur in production, as well as marketing and should be considered in the modelling.

7 | TERMS: ON-DEMAND COUPLED VS. DECOUPLED AQUAPONICS

To distinguish the two main types of aquaponics concerning water cycles, the dichotomy of coupled/decoupled systems has been introduced in recent years describing what we call permanently/on-demand coupled systems. The term decoupled evolved with changing from tightly to loosely coupled aquaponic subsystems. To our knowledge, there is no explanation for the choice of this term in the literature. However, there is a similarity to refactoring software systems,[104] where the process of dividing large monolithic systems into smaller units is called decoupling. Here, the results are systems with loosely coupled components - not 'decoupled systems'. We consider this term to be inappropriate and counterintuitive in that

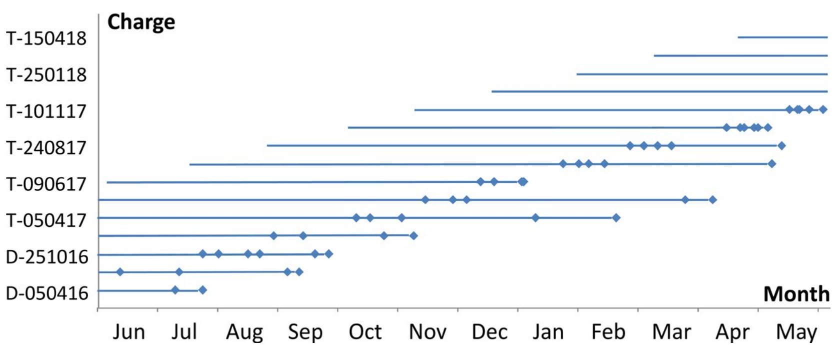

FIGURE 5 Fish production batches (lines) and sales (points) in a productive system (Waren, Germany)

subsystem coupling is the very nature of the aquaponic principle. The subsystems are decoupled by interrupting the connection between both units in the event of a production break, maintenance, pest management,[105] or accident. In the dichotomy, 'coupling' is used according to its sense: 'water and nutrient savings can be established by coupling water streams between interacting processes'[6] whereas 'decoupling' has rather the sense of 'detached', as is shown, for example, in 'these convenient fuels have allowed us to decouple human demand from biological regeneration'.[106] On the contrary to this example, an aquaponic system should be balanced and the two subsystems coordinated as well as possible. For this reason, we prefer permanently/on-demand coupled over coupled/decoupled and flag the latter as deprecated. The novel taxonomy enables a unified description of aquaponic farming facilities by coupling type attributes, for example, as 'on-demand coupled, two-way connected system', which explicitly expresses the respective setup.

8 | CONCLUDING REMARKS

Unambiguous terms and precise definitions are the foundation of any discipline. This study builds on the work already conducted by aforementioned scholars. We discussed existing dissonant aquaponic definitions and presented a revised and clarified taxon 'aquaponics' based on a well-founded and reasoned definition. Water is explicitly included as a functional element to prevent processes from being called aquaponics where dried sludge is used as fertiliser. It is justified that hydroponics is a prerequisite for aquaponics, and water or nutrient thresholds should not be part of the definition. In addition, we propose the new taxon 'trans-aquaponics', which includes *integrated aqua-agriculture systems* exploiting the aquaponic principle of driving plant cultivation by aquaculture distinct to aquaponics. Thus, both taxa are discrete sets at the same taxonomic level. We propose to aggregate them under the umbrella term 'aquaponic farming'. Concomitant, we oppose a proposal that determines 'aquaponics' overarching 's.s.' and 's.l.' taxa, because 'aquaponics' then can no longer be applied without these additions (which are not part of the related definition) as it is unclear whether the old or the new meaning of the term is used. The definitions proposed in this study have been developed bottom-up, with aquaponics as the basis, trans-aquaponics referring to it, and aquaponic farming referring to both. In a top-down approach, the aquaponic principle distinguishes aquaponic farming from other *integrated aqua-agriculture systems*.

Based on a system analysis approach, we introduce a new framework that applies coupling type and degree to describe different aquaponic farming setups in terms of qualitative and quantitative aspects of the coupling of the system units. The advantage of using this framework is its extensibility by attributes and parameters, which are neither limited to the number of different aquaponic farming units nor any specific kind of connections between them. These concepts comprise a metric in order to significantly improve the comparability of aquaponic models or real aquaponic facilities by summarising key coupling parameters (type and degree). Since the term 'on-demand coupled system' refers to an aquaponic setup more intuitively, we prefer it to the term 'decoupled system'.

For colloquial or marketing purposes, the distinction between aquaponics and aquaponic farming may not be significant: aquaponics can be used as shorthand for aquaponic farming, and an aquaponic facility can be called an aquaponic farm. However, in scientific and other (e.g. legal) contexts, trans-aquaponics can be used additionally to be more precise. An example of this is organic certification in Europe, where aquaponics is excluded, but trans-aquaponics could be approved. Another example is the usage of aquaponic farming as *nature-based solution* within the circular city concept, where it has to be considered that aquaponics is often implemented as controlled environment agriculture, while trans-aquaponics includes pond-aquaponics, aquaponic gardening or aquaculture using constructed wetland for sludge removal.

The coining of concise terms serves to overcome communication barriers and constraints, and this study is an attempt to support this process related to aquaponic farming. By the above framework, we provide a new perspective for the classification and evaluation of its technological aspects. However, more efforts are required to further refine this novel approach of comparing facilities regarding the configuration, effectiveness and sustainability of their unit coupling concerning key performance parameters of aquaponic farming.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTION

The contributions of the authors are briefly described using the taxonomy of CASRAI's CRediT definitions of contributor roles. Gösta F.M. Baganz: Conceptualisation, Methodology, Formal analysis, Writing – original draft, Visualisation, Funding acquisition. Ranka Junge: Writing – review & editing. Maria C. Portella: Writing – review & editing. Simon Goddek: Writing – review & editing. Karel Keesman: Writing – review & editing. Daniela Baganz: Writing – review & editing, Project administration, Funding acquisition. Georg Staaks: Writing – review & editing, Funding acquisition. Christopher Shaw: Writing – review & editing. Frank Lohrberg: Writing – review & editing, Supervision. Werner Kloas: Writing – review & editing, Project administration, Supervision.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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