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Ecological Restoration of Inland Aquaculture in Land-Locked Europe: The Role of Semi-Intensive Fishponds and Multitrophic Technologies in Transforming Food Systems

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ABSTRACT

Pond aquaculture and water protection in Europe suffer from conflicts, whereas multitrophic freshwater aquaculture technologies face hardships with over-regulations in Europe. As such, inland freshwater aquaculture in land-locked Europe has not given its contribution or echoed its importance in regional food system dialogues. The emphasis on marine cages and RAS-based aquaculture is enormous. Almost if they are the only viable way to carry the future European aquaculture forward. In this scoping review, we have hypothesized that semi-intensive fishponds and freshwater multitrophic aquaculture could be an overlooked component in the European food system. The analysis we present reviewed: (1) current positioning of inland freshwater aquaculture in European food system; (2) European fishponds' current positioning within food system and inland freshwater aquaculture; (3) way forward for semi-intensive European fishponds through ecological pond nutrition research; (4) ecological technologies for realizing 'net zero' aquatic foods in land-locked Europe; (5) risks and potential for making the transition. We conclude ample circular technologies and nature-based solutions in pond and multitrophic freshwater aquaculture in land-locked Europe. They have the potential to transform food systems locally with low-impact aquatic food. European inland freshwater aquaculture may be a sleeping giant among EU's planetary healthy diet ambitions. As an example, 0.25 million hectares available Central Eastern European fishponds have the potential to ecologically substitute 1 billion marine fish oil capsules (EPA + DHA in 1 kt marine fish oil) and 11.9 kt of casein (leucine from 0.45 billion litres milk) equivalents, fulfilling singlehandedly annual leucine or EPA + DHA requirements of 1.2–3 million adults.

1 | Introduction

Almost half of global food production currently depends on planetary boundary transgressions [1], including in Europe [2]. If planetary health boundaries were strictly respected, the present food system could provide a balanced diet to one-third of the global population only [1]. Essential prerequisites are redistribution of cropland ("food production zones"), improved water–nutrient management, food waste reduction, and dietary changes [1]. High-income nations (based on World Bank classification) are responsible for 74% of global excess material use, driven primarily by the USA (27%) and the EU-28 high-income countries (25%) [3]. The European Union (EU-28) accounted for 29% of excess global CO_2 emissions [4]. In developed countries, degrowth and convergence toward a need-based food system are proposed as a solution [5], especially for animal-sourced foods [6].

In general, animal-based foods are more resource-intensive than plant-based foods. Aquatic animal products potentially use fewer resources than terrestrial meat products (egg, pork, poultry, dairy, beef). Sustainably farmed fish might be as low resource intensive as some plant-based foods. Data in this regard can be found in several sources [7–9]. Aquatic origin proteins, lipids, carbohydrates, and micronutrients ("blue foods") are expected to nourish future nations [10, 11] and provide a vital component of a 'planetary and healthy diet' [12]. It is increasingly understood that farming more food from water is possible [13]. Also, aquatic food production can complement land-based production without competing for land resources [14]. Aquaculture can partially thrive on waste streams of terrestrial food systems [15, 16].

Developed and land-locked Central European countries with a high purchasing power may continue to consume "imported" aquatic foods, primarily marine, for example, Czechia, Austria, and Slovakia [17, 18]. There is little hope of what local solutions could do or if they are needed ("local–global debate") [19]. Instead, compliance with the EU water framework directive (WFD) and keeping inland waters clean [20] with a lesser focus on blue food production seems more critical. Simultaneously, these land-locked countries rely on domestic land-based aquaculture production (RAS), exploitation of captured marine resources, or intensive aquaculture elsewhere (e.g., imported salmon, frozen shrimp, tilapia, and pangas fillets) [17, 18]. In a way, local ecosystems are preserved at the expense of distant ones. There are imbalances between the EU's vision of a planetary healthy diet, national dietary guidelines, and circularity guidelines for future food system development [21, 22].

The review hypothesizes that "semi-intensive fishponds and freshwater multitrophic aquaculture" could be a solution to the European food system. It can complement the terrestrial food system and balance out the environmental impact caused by over-reliance on land-based crops, fish, or livestock production. If appropriately managed according to hydrobiological and microbial ecology principles, ponds could produce nutritious food with less inputs and emissions through their biotic and abiotic remediation capacity. These dimensions are reviewed below. The freshwater focus is also much needed to balance the many marine reviews predominating the blue foods dialogue [23, 24].

1.1 | European Food System: Current Positioning of Inland Freshwater Aquaculture

In terms of environmental health, Europe is not farming within planetary boundaries. Agriculture is one crucial contributor, of which more than 50% is linked to animal production [25]. Focusing on increasing production at any cost, with little consideration for the environment and insufficient attention to recycling resources, has brought numerous problems [25]. European annual limits for nitrogen and phosphorous losses from agriculture (limit: 2.1–6.0 Tg N; 0.07–0.19 Tg P/year), anthropized land (limit: $1.4–4.1 \times 10^6$ km^2), and freshwater use (limit: 291–840 km^3) define a safe operating space for future development of Europe's population [2]. The planetary boundaries for biosphere integrity and biogeochemical flows of nitrogen (N) and phosphorus (P) were already transgressed [26]. Agriculture's role in the exceeding limits of N and P footprint is ~87% and ~90%, respectively [2, 26]. In 2011, the European N footprint amounted to 6.8 Tg year^{-1} (5.9 Tg N year^{-1} for EU-28). European P footprint amounted to 0.13 Tg year^{-1} (0.11 Tg P year^{-1} for EU-28) [2]. With some degree of uncertainty, agriculture's role in losing biosphere integrity is estimated to be ~80% [26].

Central Europe's status quo animal food plate is far from a proposed planetary healthy diet. The planetary healthy diet advocates the consumption of at least 125 g of dry beans, lentils, peas, and other nuts or legumes per day but consuming no more than 98 g of red meat (pork, beef, or lamb), 203 g of poultry, and 196 g of fish per week—to satisfy 'protein demands' [12]. Although the proposed planetary healthy diet may not be perfect [27, 28], present animal-sourced food consumption in the Central Eastern European Region (CEER) could be globally classified as one of the worst [29]. Consumption of white meat (poultry and fish) is not associated with increased mortality, while consuming red meat is associated with an increased risk of stroke and type 2 diabetes. Fish intake, in particular, has been associated with reduced risk of cardiovascular diseases, better cognitive functions, and reproductive health [12]. Fish eaters may more likely include vegetables than terrestrial meat eaters; regular fish consumers consume more pulses, fruit, and vegetables [30, 31]. Regarding human health, the EU mortality map attributable to a diet low in omega-3 fatty acids (from fish) shows dark-red zones in predominantly land-locked central Europe. The average blood EPA + DHA levels in central Europe are also classified as "very low" [32].

Consumption of fish contributes to environmental health as well. Aquatic animal products potentially use fewer resources than terrestrial meat products (egg, pork, poultry, dairy, beef). Sustainably farmed fish may be as low resource intensive as some plant-based foods [8, 9]. On a standardized diet basis (2000 kcal, irrespective of age and gender), the vegetarians (not vegans) and fish eaters in the United Kingdom showed comparable nitrous oxide (N_2O) emissions (most potent greenhouse gas (GHG)), land use, and biodiversity impact (species extinction potential) [33]. The relative environment friendliness of 'fish as food' and its potential to deliver micronutrients like omega-3 fatty acids, vitamins, and essential minerals is now firmly established [7, 11, 34]. Recently, a global blue (aquatic food system) ambition and transition was launched [10, 35]. Regarding readiness to make such a transition, the land-locked European countries are far from ready. There is a significant gap between the ambition of the blue food system and reality checks, for example, in land-locked European countries (Table 1).

Although globally, we are eating more aquatic foods than ever – about 20.2 kg per capita in 2020, with > 21 kg expected by 2030; aquatic foods now contribute 17% of animal proteins and 7% of all proteins [35]. Unfortunately, fish production and consumption in land-locked Europe fall far behind land-locked Asian or African countries [29, 35]. As economically developed, Central European land-locked countries have a significant import dependency on aquatic foods; only 1 in 3 consumed fish are locally produced endemic species from freshwater environments (Table 1) [37]. Achieving a planetary healthy food system is more complicated in land-locked countries like Czechia due to lack of sovereign access to marine resources, environmental over-regulation, or apathy towards freshwater fish as food [36–38, 41, 42]. Taking Czechia as a typical land-locked Central European country with both EU environmental regulations and an inland aquaculture sector kept alive, a representative trend in European inland freshwater aquaculture is visible (Figure 1; left panel). Ecological pond aquaculture is not growing or being prevented from growing, while an impetus is being given to land-based recirculatory aquaculture system (RAS) farms and their expansion (Figure 1; left panel). The resultant trend in total production is stagnation (Figure 1). We reiterate the report by FAO that although aquaculture is one of the fastest-growing food production sectors globally, it is not in Central Europe [43].

Overall, there are 16 such landlocked countries in Europe: Andorra, Armenia, Austria, Belarus, Kosovo, Czechia, Hungary, Liechtenstein, Luxembourg, North Macedonia, Moldova, San Marino, Serbia, Slovakia, Switzerland, and Vatican City. Among them, the World Bank (hyperlink) lists only six as middle-income countries (Armenia, Belarus, Kosovo, North Macedonia, Moldova, Serbia); the 10 are economically developed with a high purchasing power as of 2021–2022. With available data from Eurostat (fish_aq2a), the land-locked European countries have not changed much regarding inland freshwater aquaculture production (Figure 1; right panel). Between 2016 and 2022, production from RAS, fishponds, tanks, raceways, cages, and pens combined (within European inland) have not changed significantly (t-statistic -0.125, $p = 0.902$; Figure 1 right panel). The current positioning of European inland freshwater aquaculture seems dormant within the EU food system.

1.2 | European Fishponds: Current Positioning Within the Food System and Inland Freshwater Aquaculture

A common feature of all land-locked European countries is their historically maintained "pondscapes." Their riverine

TABLE 1 | Blue food system ambition and reality-check in land-locked European countries.

Dimension	Ambition	Reality-check
Per capita fish consumption	2 portions week^{-1} (200 g portion^{-1}); 19–20 kg capita^{-1} year^{-1}	< 1 portion week^{-1}; 6–8 kg capita annum
Annual per capita freshwater fish production	No ambition	2 kg capita^{-1} year^{-1}
Per capita edible freshwater fish availability	No ambition	1 kg capita^{-1} year^{-1}
Imported marine fish to local freshwater fish	No ambition (but ideally, 1:1)	2.75: 1
Meat and fish balance in planetary healthy diet	1:1 (chicken: fish); 0.5:1 (red meat: fish); 2:1 (chicken: red meat)	5:1 (chicken: fish); 9:1 (red meat: fish); 0.5:1 (chicken: red meat)
Minimum per capita EPA + DHA intake	250 mg EPA + DHA day^{-1}	218 mg EPA + DHA day^{-1}
Omega-3 index of the adult human population	> 8%	2.5%–3.5%

Source: [12, 29, 32, 36–40].

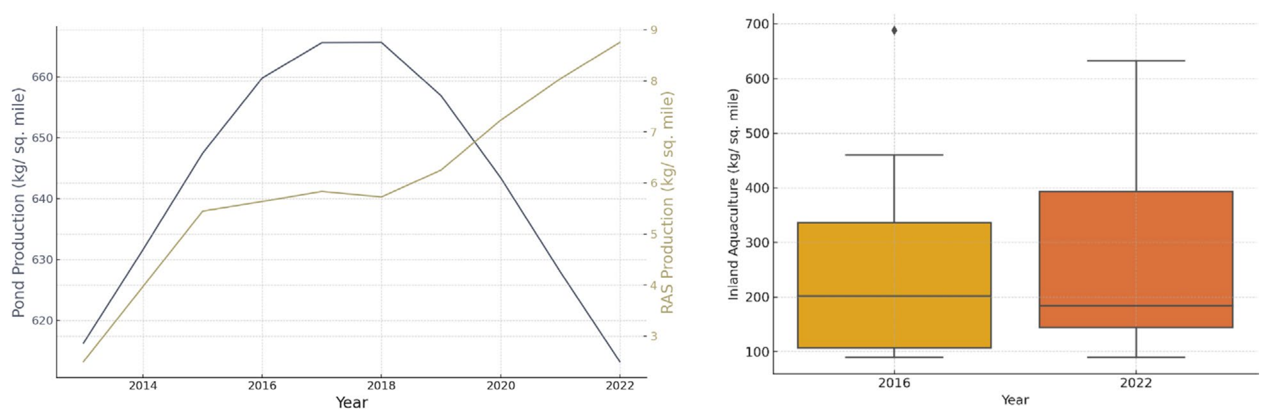

FIGURE 1 | Left panel: Trends in land-locked aquaculture in Czechia (Central Europe) having both EU environmental regulations and aquaculture priorities in place. Right panel: Distribution of inland aquaculture production of available predominantly land-locked European countries in Eurostat fish_aq2a (Czechia, Germany, Hungary, Austria, Poland, Slovakia, North Macedonia, Serbia) between 2016 and 2022 ($p > 0.05$).

capture fishery (commercial) is not very established like in Asia or Africa, drinking water reservoirs are highly preserved, and land-based aquaculture is in its infancy or competing with agriculture/energy needs. The wetlands converted to fishponds are the backbone of national aquatic food production [44–46]. Historically, most Central European ponds are large (> 2 ha) and shallow (1–1.5 m) but drainable. They are drained to facilitate harvest. The pond bed is sometimes exposed to overwintering (every 1–2 years) and exceptionally dried in the summertime (every 4–5 years) [47, 48]. Fish production from such systems, primarily cyprinids (carp) by traditional semi-intensive production methods, is considered a national heritage and has been practiced since the medieval era [41, 49–53]. Over time, pond-based aquatic food production has stagnated (for economic reasons) or purposively curbed (for environmental reasons) in these regions [41, 54]. For example, the market prices of pond-farmed carp have decreased significantly in most European countries. Present farm-gate prices of carp in Czechia and Germany are ~2–2.5 € kg^{-1} live weight or even lower (1.9 € kg^{-1} live weight) in Hungary [41, 55]. There has been some debate between environmentalists and carp farmers concerning the eutrophication of water bodies. Supplementary feeding has been tagged as a 'harmful substance' applied to fishponds, increasing nutrients associated with carp stocking and poor nutrient use efficiency by carp or fishponds have been discussed [54, 56–59]. While discussing the management issues, it is often overlooked that the GHG emission intensity of fish from the pond (< 5 kg CO_2-eq per kg consumable weight) is lowest (with poultry) among other popular animal meat (small ruminants, big ruminant) [41, 60]. Therefore, shifting to a diet with more pond fish and chicken, partly replacing red meat, may shift overall diets towards lower GHG emissions in these regions [33, 60].

Recent data (2022–2023) by the agency EUMOFA show only Hungary (total fish production = 27,600 tons; 1.7 kg edible fish $capita^{-1}$ $annum^{-1}$) and Czechia (total fish production = 24,300 tons; 1.4 kg edible fish $capita^{-1}$ $annum^{-1}$) are top producers of edible fish biomass from inland aquatic resources (ponds), among the land-locked European countries. In Hungary, 78% of production comes from ponds, while 22% occurs in land-based tanks and raceways, and the production is dominated (60%) by catfish. In Czechia, about 90% of the production is pond-raised common carp. The remaining 10% are herbivorous Asian carp and predatory fish, or rainbow trout, African catfish, and tilapia produced in RAS and flow-through raceways. Czechia is the closest country to fit a low-impact food system ideology such as "low trophic level farming." In the neighboring countries, Austria (total fish production = 4500 tons; 0.3 kg edible fish $capita^{-1}$ $annum^{-1}$) and Slovakia (total fish production = 4000 tons; 0.4 kg edible fish $capita^{-1}$ $annum^{-1}$), the production is too low even to discuss. Besides, an opposite preference is there. More trout and African catfish (60%–66% of the total production) are produced in RAS and flow-through systems than omnivorous carp in ponds (15%–29%). Most ponds are also managed in an "organic" and extensive mode to promote aesthetics and recreation. The key motivation is to promote environmental services provided by ponds, including non-food services. Here, it might be helpful to note that ecosystem services (offered by ponds) can be promoted with partly fed semi-intensive aquaculture, too; unfed extensive mode of farming is not a pre-condition [41, 61–64].

The fish production per unit area in ponds average 0.5 ton ha^{-1} is low. This gives an environmentally healthy image for the European pond aquaculture sector. The nutrient footprint of Central European fishponds (~9.4–10.8 kg N ha^{-1}, ~2.7–3.2 kg P ha^{-1}) is 1.5–4 times lower than EU crop-livestock sectors, with positive ecosystem services (~2375 € ha^{-1}) provided by carp ponds. For European standing waters (lakes), target concentrations between 0.5–1.8 mg L^{-1} TN and 10–60 μg L^{-1} TP signify a good ecological status (GES). However, 61%–64% of monitored lake sites in the EU have failed to qualify for GES, even after 30 years of WFD implementation. Fertilizer-based agricultural nutrient input has been deemed a culprit. Even significant agriculture load reductions cause minor improvements only. Without supplementary feeding, the natural production from temperate Central European fishponds is ~0.1–0.3 ton fish biomass ha^{-1}, often assumed as the "natural carrying capacity" [41]. With supplementary feeding, production from fishponds is doubled above the carrying capacity [41, 65]. Following this, the national aquaculture policies in the region (e.g., Czechia) suppose that more aquatic protein and lipids cannot possibly be extracted from ponds for the human food chain. One of the reasons is believed to be the shorter duration of the vegetative season (lasting 6–7 months; 15–29 °C water temperature), during which most of the biomass gain is realized. It is preceded or followed by a thermally cued (≤ 12°C) non-growing or non-feeding phase for most pond fish and frozen overwintering phase [65–68]. The other, perhaps the most influential reason, is the nutrients (nitrogen, phosphorus) and concerns surrounding water quality degradation [54, 69, 70]. Following this thermal cycle, the mineralization processes happening in temperate Central European fishponds are also inhibited or ceased for up to 4–5 months. Organic matter, be it autochthonous (fish excreta, detritus, legacy sediment, aquatic macrophytes, etc.) or allochthonous (inflow from the catchment, water source, supplementary feed, wildlife droppings, etc.), tends to accumulate in these systems. Aquaculture ecosystem services are increasingly being recognized for fishpond systems [41, 61, 71, 72]. The government supports Austrian pond aquaculture producers with 450 EUR ha^{-1} fishponds with an additional 100 EUR ha^{-1} if they farm ecologically. Ecologically, this means stocking carp below specified stocking density limits and agreeing to reduced productivity (annual yield) from their system. Also, it preserves the aesthetics, biodiversity, ecology (clear water state), and compliance with N and P limits in outlet water (Bundesministerium Landwirtshaft, Regionen und Tourismus, 2022). Often, such policies fail to see the merit of fishponds in serving the human food system and restoring a nutritious diet (public health) locally with the least emissions or resource use. For example, semi-intensive European fishponds could be an ecological pathway for mining EPA + DHA locally, thanks to its ecosystem components (natural food web) and pond fish bioaccumulation pathways that need some tailoring [37]. At the expense of keeping or restoring Europe's inland freshwaters pristine, nutrient pollution and environmental damage occur elsewhere (when imported fish are consumed for the same nutritional benefits). A detailed analysis in this regard can be found recently [37].

1.3 | Way Forward for Semi-Intensive European Fishponds: Current Pond Nutrition Research

Aquaculture is mainly fed fish production [73]. The inland semi-intensive fishponds are not fully fed. They thrive partly on the natural food web and upcycling ecosystem nutrients to the human food chain edible form [41, 49, 60, 65, 68], and in this process, they also offer various ecosystem services [41, 63, 64, 74]. Even what is considered today as undesirable fishes in Central European fishponds [66] have a consumption history in other parts of the world [75]. The price of producing fish in European fishponds is growing much slower than the cost of managing pond fish farms, so the profit margin is shrinking over time [55, 76]. Another challenge is climate change [77]. For example, the CERES report suggests carp farmed in Central European ponds may have higher growth and better profit by 2040–2059. However, it would also be resource-demanding—requiring more feedstuff per production cycle [78]. Another aspect is the delayed overwintering period due to changing climate [79], which might require an additional 1-month supplementary feeding (unnecessary now but relevant later) in fishponds for the entire region.

Opposite to RAS, fishponds can provide an easy alternative to upcycle circular ingredients or low-opportunity-cost biomass (LOCB) as food [80]. The 'low opportunity cost biomass' (LOCB) is defined as discarded biomass, plant residues, by-products, and food loss and waste, typically competing less for land or natural resources and representing an important human-inedible feed resource for livestock production [81]. Even if the FCR of a pond feed is poor (> 2) due to its less refined nature or LOCB ingredients [80], the wasted nutrients (C, N, P) can stimulate pond food web productivity (zooplankton). They may be reflected in harvested fish biomass [65, 82, 83]. Also, the supplementary pond feeds are not complete fish diets alone; instead, they strive to be complete by complementing the natural food co-ingestion by pond fish [37, 60, 65, 68]. The nutrient density of such feed could well be ≤ 25% protein and < 0.25% bioavailable P to prevent eutrophication [54]. The challenge is to make pond feed mixtures [47, 65, 84], derived from LOCBs, with a C:N:P ratio that simultaneously stimulates the pond food web and masks deficiencies in natural food. So fewer free nutrients (N and P) accumulate in the system, causing eutrophication, and excess C is either respired aerobically or stored in the food web or sediment organic matter (even for later use in agriculture) [60, 85].

In Central European Pond farming, a balanced pond feeding concept [68] has been developed to upcycle local LOCB resources to produce nutritious food from the ponds in harmony with the natural food web [37, 65, 68]. Aquatic microbes and enzymes enhance nutrient bioavailability or digestibility of LOCB pond feeds [86]. However, physiological constraints in the body (e.g., consumer homeostasis, improper ecological stoichiometry of nutrients/energy) cause nutrient leakage back into the water [87]. By balancing the nutrients and energy in natural food externally, one can make fish stocks as nutrient sinks [87]. Also, by providing additional substrates for the zooplanktonic-benthic food web to proliferate, one can produce cleaner food in ponds [85, 88]. Thus, more protein is produced with less nutritious feed, and N and P are harvested via fish biomass and kept in the zooplankton-zoobenthos too [85]. Some ongoing examples in Czechia can be found for reference (see BioRural Toolkit). For example, balanced pond feeds that allow production in harmony with the natural food web were developed and tested successfully: (a) beginning-of-season (April–June) feed having low protein (< 15%), high digestible energy (290 kcal 100 g^{-1}; starch 55%, lipid 3%), low-P (< 0.3%) that would help spare natural food and suppress the non-fecal losses of their valuable nutrients; (b) end-of-season (July–October) feed having balanced protein (28% protein, Lys > 1.6%, Met > 0.5%) to energy (274 kcal 100 g^{-1}; starch 20%–33%, lipid 5%–6%), amino acids profile ($DIAAS_{Lys} > 55\%$; $DIAAS_{Met} > 50\%$) that complement natural prey, partly fermentable fibers in carp gut (NDF:ADF ratio > 2:1), and isogenous or less P content than natural prey (< 0.9%; below carrying capacity of ponds) to serve the role of feed that serves both fish (by complementing ingested natural food in gut) and also stimulate the pond food web. This system gives higher yields up to 1.5 ton ha^{-1}, FCR of ~2, with a total N, P concentration in pond water similar to traditional cereals feeding, improved water clarity, and preventing the collapse of keystone species in planktonic ecology such as daphnia throughout the season. Thus, more nutritious fish fillets can be obtained with less supplementary feeding, suppressing eutrophication, by a balanced pond feeding in harmony with the natural food web (Roy, Mraz, unpublished data).

An eco-efficient pond nutrient excavation strategy, based on natural prey availability and respecting feeding cues (temperature and dissolved oxygen), involves the supply of non-protein energy when natural food is abundant and supplying amino acids + energy (for fish and food web both) when natural food is scarce. By adjusting fish stock densities and adaptive supplementary feeding, it is possible to maintain a functioning and unbroken (links) food web in fishponds. A broken food web means an unhealthy ecosystem, with collapsed keystone species, unbalanced nutrient ratios of C, N, and P, preventing integration of excess nutrients in the natural food web (imbalanced nutrient stoichiometry can be natural but also man-made), and imbalanced microbiome (e.g., cyanobacterial blooms, methanogens, etc.) [66, 70, 89–91]. Such fishponds with imbalanced stoichiometry are not efficient nutrient converters or generators for a food system. A combination of polyculture, environmental enrichments (zooplankton-benthos refuge, fiber-rich pond feeds), triggering of EPA + DHA biosynthesis in pond fish (by creating alpha-linolenic acid precursor gradient), and fish processing oil-based finishing feeds could make pond farmed fish fillets deliver > 250 mg EPA + DHA 100 g^{-1} portion and antihypertensive fish protein peptides (rich in leucine [92]; ~1 g leucine 100 g^{-1} portion) in an eco-friendly way and locally [37]. Other aquaculture systems may be unable to do so efficiently without nature's help. Natural prey items in pond fish diet [93, 94] can be imagined as equivalent to high-value fish meal and fish oil used in RAS diets; when fed alone, they show poor nutrient bioeconomy, but when a diet is formulated around them with the correct principles, they show high nutrient bioeconomy. Recent data in this regard is available [37, 68, 87, 95], including classic records [96–101]. Also, the pond food web continuously generates *de-novo* food by primary productivity. However, the trophic transfer efficiency from pond food web to fish is poor [102]. Recently, it has been realized that by sparing and boosting large-bodied zooplankton-zoobenthos from collapsing through supplementary pond feeds made up of agri-food by-products (formulated by nutritious pond and balanced pond feeding concepts; see BioRural Toolkit), more could be produced from fishponds with less inputs.

1.4 | Ecological Technologies for Realizing 'Net Zero' Aquatic Foods in Land-Locked Europe

The circular approaches and bio-based solutions are well adopted in the aquaculture research community. It is now waiting for a widespread application of those innovations [103]. Most pollution from aquaculture operations is a function of system design or production environment [104], and they could be fixed. Some available circular technologies and nature-based solutions that allow the EU's inland aquaculture to be 'net neutral' and 'resource efficient' are summarized in Table 2.

Some earlier efforts to strengthen circularity in inland aquaculture of the EU by the land-locked countries need special mention. The approach so far has been chiefly changing 'design.' For example, a combination of intensive systems (like RAS, cages, raceway) with fishponds or connecting water flow of several fishponds [62]. Among these are a few solutions worth highlighting for land-locked Central Europe, which aims to upgrade traditional pond farming into a modern industry. Firstly, via integration of ponds with constructed RAS in the vicinity. The benefits can be many: (a) use ponds to recycle RAS effluents [127, 132]; (b) shorten the culture period to grow carnivorous fish to market size and to improve survival, e.g., pikeperch (*Sander lucioperca*) [128, 138]; (c) improve land (space) use efficiency of future aquaculture expansion. When RAS effluents (sludge) were mixed with natural sediment in ponds, the ammonification and nitrification rates were significantly accelerated in Hungary. In the case of ammonification, the time was reduced from 4–5 weeks to 2–3 weeks. In addition, nitrification peaked in 2 weeks instead of 5 weeks [125]. Another approach is to link ponds in a linear cascade [67, 124] to upcycle waste nutrients discharged from the first pond into aquaculture crops of different species stocked in the other ponds along the cascade. The benefit is a reduced nutrient concentration in the effluent from the last pond in the cascade, which can be directly drained into natural receiving waters. In Poland, this system could recycle or retain up to 51% of input C, 75% of input N, and 50% of input P. Despite high nutrient retention efficiencies, the total load of nutrients at exit can still reach high levels, due to the nutrient richness of inflowing water to the cascade pond system or manuring application [124]. Without manuring and with balanced pond feeding concepts [68, 82, 83], pond cascade systems could be made viable. For example, a pond cascade system in Czechia that was not manured achieved 84% P retention (inflow water 0.5 mg total-P L^{-1} to outflow water 0.08 mg total-P L^{-1}) [67, 139]. Tank-by-pond or cage-in-pond systems constitute a third approach developed in Hungary and Slovenia (SilGen project). These 'hybrid systems' rely on ponds as the biological filtration unit. The tanks or cages are operated intensively while covering a small area of the total pond system. Uneaten feed from these intensive units can be eaten by carp scavenging around the cages or tanks, while faeces or metabolic wastes from the cages or tanks boost the natural pond food web productivity without manuring interventions.

TABLE 2 | Available technologies for ecological restoration of inland aquaculture in the EU.

Technology	Case examples
IMTA (integrated multitrophic aquaculture)	IMTA ponds with polyculture of native species [105, 106]; pen culture (polyculture) at the margins [50]; low-intensity cage culture [107, 108]; floating raft-based aquatic vegetable production [109]; shellfish culture in submerged cages [110]; trap-based capture fisheries for undesirable fishes intermittently [111, 112].
Trading of low opportunity cost biomass (LOCB[a]) or local food system by-products	LOCBs, which cannot enter the local human food chain directly [113], may be traded as feed for livestock, poultry, or aquaculture. For aquaculture, more refined feed ingredients would go to RAS while less refined ingredients could be directed to fishponds [80, 114]; freshwater fish processing discards fed to poultry [115] and poultry slaughtering discards fed to fish [116]; aquatic macrophytes from ponds fed to ruminants [117], crustacean or bivalve shells fed to poultry [118].
Environmental enrichment	Semi-intensive fishponds could switch to polyculture models with natural or artificial periphyton beds [88, 119]; preservation of emergent littoral macrophytes [120]; duckweed propagation [121].
Integrated farming systems (IFS) and hybrid ponds	Integrated farming with livestock and horticulture [122]; connecting pond with RAS systems (Halasi-Kovacs, 2021); pond sludge captured and sold for fertilizing nearby agricultural fields [123]; pond cascade systems for high C, N, P use efficiency [67, 124]; splits ponds, pond-in-pond, tank-by-pond [62, 125]; cage-in pond [126] or RAS-pond integrations [127, 128]; in-pond raceway systems [129].
End-of-pipe or bio-refinery solutions	RAS connected with plant or biofloc [130, 131] or vermicomposting [132]; duckweed culture [121]; aquaponics (Baganz et al., 2021) integrated with insect [133] rearing on vegetable wastes, algae production or duckweed [134, 135]. Sludge from RAS or their leachate is used as fertilizer [136, 137].
Stoichiometric feeds for ecology	Balanced pond feeding concept for temperate European fishponds [68]; nutritious pond feeds concept [85].

[a]LOCB is defined as discarded biomass, plant residues, by-products, food loss, and waste, typically human-inedible but edible for livestock.

These systems aim to fulfill 'net zero' agendas at farm level, while improving resource use efficiency.

Aquaculture's resource use efficiency at the food system scale is also looked at [16, 114, 140]. Results indicate aquaculture could potentially solve problems with terrestrial food systems by, for example, upgrading excess crop residues or bio-refinery products regionally that livestock cannot upcycle alone or by integrating livestock by-products that cannot be fed back to livestock [140] into aquaculture products. The local agri-food system's organic waste streams from agriculture and livestock, fruits and vegetables, bakery, and brewery [113] could aquaculture operations nearby. Some examples of direct use (Figure 2) may include livestock by-products (e.g., organic manure for ponds, poultry by-products for aquafeed) and agricultural by-products (e.g., oilseed cakes after oil extraction, cereal remains post brewing/ distillation, carbohydrates from surplus, unsold tubers). Indirect usages of organic waste streams (Figure 2) may include products or co-products derived from biorefinery (composting, fermentation, insect and algae culture) [133, 134, 141]. A significant valorization pathway in Central Europe could be 'farm-made feeds' for supplementary feeding in fishponds [80, 84]. For example, unsold bakery/ bread discards, extrusion wastes from factories manufacturing morning breakfast cereals, microbial protein derived from fermentation industries, oilseed expellers, broken peas and beans, brewery/ distillery spent grains, malt sprouts, etc., can be made into compound farm-made pellets; predominated by energy-rich ingredients at the beginning of the season and protein-rich ingredients at the end of the season [68]. Rapeseed expeller meal has the most complementary protein quality to natural food, as measured by the Digestible Indispensable Amino Acid Score (DIAAS) of lysine, methionine [65], closest to that of natural prey items such as cladocerans, copepods, and chironomids in fishponds (Kuebutornye, Roy unpublished data). Rapeseed expeller meal's complex fibers could also be partly fermented in pond or pond fish carp gut having high cellulolytic activity [86] or stimulate pond food web by principles of ecological stoichiometry theory (high C:N, C:P ratios of fish faeces) [85]. There are also food system by-products like spent coffee grains, fruit peel, and spent hops (*Humulus lupulus*) from local breweries that may not serve as feed ingredients per se but may serve as sources of bioactive compounds [142].

1.5 | Risks and Potential for Making the Transition

By-products availability around the year may be a concern. Due to their perishable nature, they may not be stored for long periods. For example, we assessed resource availability and possibilities for circular aquaculture in Czechia (land-locked territory). The results are provided in Table 3, with methods and data sources in supplementary text. Our preliminary comparison (Table 3) suggests that (a) local forage fishmeal may supplement and replace marine fishmeal presently being used in RAS; (b) local food system waste streams may supplement the use of farmed soybean and faba bean in intensive aquaculture; (c) farmed rapeseed oil used in aquaculture may be substituted to some degree by locally sourced, waste stream derived oils; (d) carbohydrate or starch derived from local waste streams of the brewery, fruits, vegetables, and bakery origins may substitute some cultivated cereals use in ponds; (e) there might be room for improved waste valorization (poultry by-products, agricultural by-products) for intensive aquaculture. Some anti-nutritional factors are often present in circular ingredients [143, 144]; even high ash, lipid, or fiber content in insects or animal by-products [116, 145]. They may retard aquaculture's growth via reduced fish growth, poor

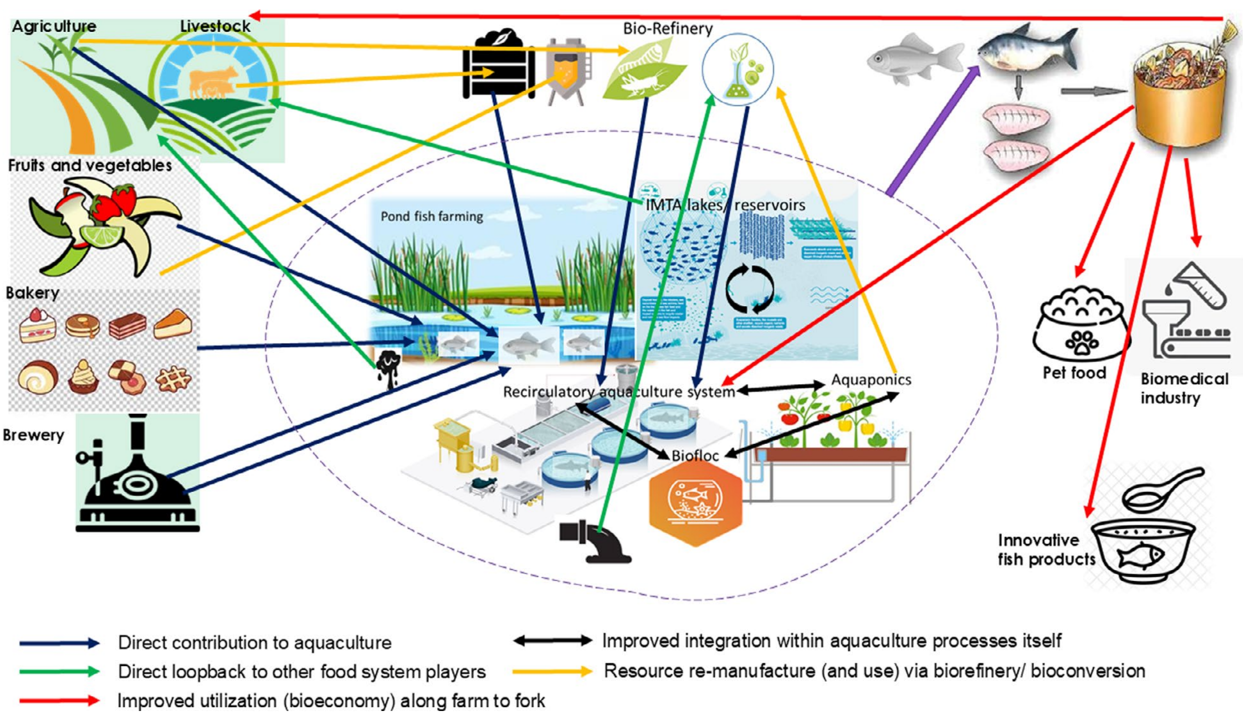

FIGURE 2 | A local bubble archetype of future materials (nutrient) flow for planetary healthy blue foods in Central Europe (conceptual schematics).

TABLE 3 | Current food system-derived resource consumption (basic estimates) of Czech aquaculture and circular-origin resource availability (conservative estimates) for enabling planetary healthy blue foods. Estimates are based on a conceptual material flow framework (see text).

Current resources in use					Circular-origin resources available locally				
Ingredient name (*purpose in aquaculture*)	**Current source**	**Mode of use**	**Amount consumed, dry matter (tons)**[d]	**Threatening planetary health boundary**	**Alternative (circular) source**	**Circular amount available (tons)—original matter**	**Circular amount extractable (tons)—dry matter equivalent**	**Dry matter amount apparently available (tons)—post competition**	**Remarks**
Fish meal (*animal protein source in aquafeed*)	Wild (Marine)	Direct raw material	423.3	Biodiversity	Forage fish-derived fish meal from capture fishery	1215.5	413.3[b]	136.4[c]	Local forage fishmeal may replace 1/4th of marine fishmeal
Soybean, Faba beans (*plant protein sources in aquafeed*)	Cultivated	Direct raw material	951	Land use, biogeochemical (N, P) cycles, climate change (via agriculture)	Local oilseed cultivation waste stream (e.g., rapeseed cake)	371419[a]	289707[b]	95,603[c]	Local waste streams may sufficiently offset the use of farmed soybean and faba bean in aquafeed
					Local FAB waste streams of animal (protein) origin	80500[a]	36225[b]	11954.3[c]	
					Local waste streams of breweries (e.g., corn gluten meal, corn germ meal, microbial protein)	41283[a]	28898.1[a]	9536.4[c]	
					Local supermarket retail waste—meat and fish (e.g., Tesco)	183.7[a]	73.5[b]	24.2[c]	
Cereals - wheat, corn, triticale (*carbohydrate, energy, filler sources in aquafeed; supplementary feed in pond fish farming*)	Cultivated	Direct raw material	72727.8	Land use; altered N, P cycles; climate change (via agriculture)	Local FAB waste stream of fruits and vegetable origin	96000[a]	38400[b]	12,672[c]	Local waste streams of the brewery, fruits, vegetables (potatoes), and bakery origins may replace more than half of the cultivated cereals used in aquaculture
					Local FAB waste stream of bakery origin	35000[a]	24500[b]	8085[c]	
					Local waste streams of breweries/ distilleries (e.g., corn DDGS)	107217[a]	75051.9[a]	24767.1[c]	
					Local supermarket retail waste - vegetables, fruits, bakery products (e.g., Tesco)	1061.1[a]	583.6[b]	192.6[c]	

(Continues)

TABLE 3 | (Continued)

Current resources in use					Circular-origin resources available locally				
Ingredient name (*purpose in aquaculture*)	**Current source**	**Mode of use**	**Amount consumed, dry matter (tons)[d]**	**Threatening planetary health boundary**	**Alternative (circular) source**	**Circular amount available (tons)—original matter**	**Circular amount extractable (tons)—dry matter equivalent**	**Dry matter amount apparently available (tons)—post competition**	**Remarks**
Poultry meal (*animal by-product protein source in aquafeed*)	Circular origin	Industrial by-product utilization	274.2	None; already circular	Local FAB waste streams of animal (protein) origin	80500[a]	36225[b]	11954.3[c]	There is perhaps 'more scope of waste valorization' than already being done
Corn by-products (*plant by-product protein/ carbohydrate source in aquafeed*)	Circular origin	Industrial by-product utilization	953.8	None; already circular	Local waste streams of distillery (e.g., corn gluten feed/ DDGS, corn gluten meal, germ meal)	148500[a]	103950[b]	34303.5[c]	
Rapeseed oil (*vegetable oil source in aquafeed*)	Cultivated	Direct raw material	59.6	Land use; altered N, P cycles; climate change (via agriculture)	By-product from local forage fish valorization (e.g., freshwater fish oil)	41.3 (oil)	—	13.6[c]	Farmed rapeseed oil may be replaced 1/4th by local freshwater fish oil or corn oil.
					By-product from ethanol (brewery) production process (e.g., corn oil)	11,664 (oil)	—	3849.1[c]	

Note: Methods and data source in supplementary text. Red shade indicate current resource consumed. Yellow shade indicate alternative circular resources available.
Abbreviations: DDGS, Distillers dried grains with solubles; FAB, Food and beverage; IMTA, Integrated multitrophic aquaculture.
[a]Values are half of the original amount of waste stream produced. Considering if at least half (50%) of the waste stream is actually recoverable (valorized).
[b]Original matter to dry matter conversion using the following coefficients: fishmeal 0.34, oilseed cake (post extraction) 0.78, animal (meat/carcass) wastes 0.45, brewery wastes (spent solids) 0.70, retail meat and fish 0.40, retail fruits and vegetables 0.40, bakery products 0.70.
[c]Considering steep resource competition of 70% on the available dry matter by livestock, biofuel, and biofertilizer industries combined. Only 30% of available dry matter is competition-free and used in local aquaculture (without resource conflicts with other food system players).
[d]Considering standard FCR (1.6) of a commercial mid-protein level (~37%), Tilapia pre-grower feed recipe and accounting for +30% ingredient losses occurring at extrusion plant.

health, welfare, or even mortality. It might reduce the sector's protein efficiency ratio (PER) and increase the feed conversion ratio (FCR). The mere presence of circular-origin resources (feedstuffs), especially of low trophic levels, in the territory of regional food systems does not guarantee they would be fit for supporting inland aquaculture. Local producers and consumers avoid carp fed on corn or maize (*Zea mays*) as they develop yellowish belly fat and muscles. It is considered ugly and distasteful. Their use is not practiced in many Czech and German fishponds (Füllner, 2015, Zdenek Adamek *persn. comm.*, Martin Oberle *persn. comm.*). Because corn oil also retains the same yellow color, it might struggle to find its use in aquaculture, even though it is available in large quantities in a brewery region like Central Europe and is only useable for carp.

The last critical aspect is improved utilization of inedible biomass losses along local aquaculture's farm-to-fork [36]. It may require integration with pet food, the pharmaceuticals industry, or value-added fish products [146–148]. It is recommended that farmed fish biomass be upcycled to the human food chain as much as possible. A current example is utilizing a baadering/mincing machine to prepare minced fish flesh from the filleted carcass and convert them into low-cost value-added products like sausage and balls. Traditionally, the use of various fish parts for soups (e.g., '*Halászlé*' or '*Rybí polévka*' recipes) is also quite widespread [36]. However, some discards can still occur due to microbiological, safety, or consumer acceptance. Fish slaughtering discards can source fish oil, enzymes, peptides, and biopolymers [149, 150]. For example, we estimated farmed fish biomass (inedible) losses from farm to fork in Czechia. A detailed breakdown is provided in Table 4, with methods and data source in supplementary text. Conservative estimates suggest that dry matter or oil derived from farm-to-fork losses may partly supplement marine fishmeal and fish oil consumption in Czech aquaculture. It is estimated that the pet food industry in Czechia may have utilized more fish processing by-products (meal and oil) than Czech aquaculture itself via fish feeds (Table 4). There are ways in which fish slaughtering discards could feed local aquaculture via fish feed, such as fry feed or finishing feed [151]. As improved resource use efficiency through waste valorization initiatives will be encouraged, circular aquaculture would increase feed and food safety risks [25, 152]. There are significant microbial health hazards when we consider recycling food system waste as animal (here, fish) feed. The hazards may include parasites, mycotoxins, pathogenic bacteria, viruses, and even infectious (deadly) prions or chemical contaminants [116, 146, 153, 154]. Some threats may be neutralized by adequate heat treatment, hydrolysis, oxidation, or bioprocessing. However, a few of them may withstand such processes until the organic matter is destroyed (incinerated) [116, 154, 155].

Europe's freshwater use has not breached the planetary health boundary and lies much below the European limit for a safe operating space for future generations [2]. It indicates the potential of a blue-based bioeconomy in the future [17, 156] while reducing the pressure on land and mitigating footprints as much as possible. European pond aquaculture, ubiquitously carp production in fishponds, rapidly intensified during 1960–1990 [157]. Recently, much of the production was downscaled for environmental concerns, and present-day fishponds are limited much by environmental laws. Restrictions exist on using inputs to increase productivity (e.g., inorganic fertilizers are prohibited, organic manuring is restricted), including the prohibition of supplementary feeding in some fishponds (e.g., ponds in Natura 2000 areas) to restricted supplementary feeding. Restricted pond feeding includes permitted use of 'plant-origin' feedstuff only, apathy towards commercial fish pellets, or prevention of 'circular origin' feedstuff in ponds (e.g., brewery wastes in the original matter, unsold bakery products, vegetables, etc.). However, restrictions on pond aquaculture were not counterbalanced by a relative increase in intensive RAS (recirculatory aquaculture system) production. RAS contributes < 10% of national fish production, and poor economics have impeded its development [38, 158].

2 | Limitations and Knowledge Gaps

Fundamental limitations and knowledge gaps are listed below:

- Eurostat database has missing or withheld data on inland aquaculture production, available water area, or volume from which inland aquaculture is derived.
- Lack of blue food system ambitions and goals involving inland freshwater aquaculture in the EU.
- Data on aquaculture yield of different circular multitrophic systems under temperate European climatic conditions show that the volume of LOCBs available for upcycling is missing.
- Nature-based semi-intensive freshwater aquaculture in the EU and their success and failure stories are not widespread knowledge.
- There is much information on environmental expectations from inland standing waterbodies, but there is a lack of knowledge on their food production or LOCB upcycling potential(s).
- Aquaculture is predominantly seen as the loading of nutrients in aquatic systems, but natural food web and ecological stoichiometry respecting pond aquaculture could be regenerative, too.
- Hybrid ponds (coupling intensive-extensive aquaculture) are proliferating in the EU, with limited published data on performance(s). The standard package of practices is yet to be developed.
- Although reasonable, some technologies listed in Table 2 will require a careful assessment of feasibility.

3 | Conclusion and Outlook

In the last few decades, total fish production has significantly increased in all the continents except Europe. EU aquaculture production has only increased by +6% (since 2007), reaching 1.2 million tonnes in sales volume and 4.1 billion € in turnover in 2018 [43, 159]. EU still has a significant import dependency on the aquatic foods it consumes, and little is contributed by its domestic fishery production—a stagnant or shrinking inland freshwater

TABLE 4 | Detailed breakup of farmed fish biomass losses (basic estimates) along the farm-to-fork value chain in Czechia and potential valorization (conservative estimates) for improved bioeconomy.

S. No.	Farm-to-fork stage	Particulars	Available amount (tons)	Amount lost (tons)	Comparison
Status quo resource consumption					
1.	Locally farmed fish (tons)	Farmed carp from ponds	19,158	—	(1). Dry matter or oil derived from farm-to-fork losses may supplement 1/4th of marine fish meal and fish oil consumption in Czech aquaculture.
2.	Post-harvest losses (tons)	20% post-harvest losses due to spoilage or discards	—	3831.6	
3.	Apparently available fish (tons)	Fish available for rendering/processing for human consumption	15326.4	—	
4.	Human edible fish (tons)	Up to 54% of available fish biomass as slaughter yield	8276.26	—	
5.	Human inedible fish (tons)	Slaughtering discards at least 46% of available fish biomass	—	7050.14	
6.	Total farm-to-fork losses (tons)	Sum of post-harvest losses due to spoilage, discards, and slaughterhouse losses	—	10881.74	
Potential waste valorization					
1.	Circular amount extractable (tons)—dry matter equivalent	Total losses converted to dry biomass with an average 40% dry matter.	4352.7	—	(2). Dry matter derived from farm-to-fork losses may cover 15%–30% of fish consumption in Czech pet foods
2.	Minimum circular amount available - dry matter (tons)	If at least 50% of circular dry matter is usable/valorised	**2176.35**	—	
3.	Circular amount of fish oil extractable (tons)	If 20% of total losses dry matter consists of viscera, brain, eyes, gills; and a further 20% of organs dry matter consists of oil	174.11	—	
4.	Minimum circular amount available - oil (tons)	If at least 50% of circular fish oil is usable/valorized	**87.05**	—	

Note: Methods and data source in supplementary text. Red shade indicate current resource consumed. Yellow shade indicate alternative circular resources available. Bold value indicate local circular fish meal and fish oil available.

aquaculture in Europe [17, 18]. Based on the review, the EU inland (freshwater) aquaculture should contribute more before it is too late. With available ecological technologies and environmental consciousness instilled by the EU's water and biodiversity protection directives, European fishponds and inland multitrophic aquaculture could help achieve the EU's planetary healthy food system ambitions faster. An estimate of such potential based on European fishponds alone [data: [37, 41, 68, 160]] is given below:

1. Central Eastern European region (CEER) presently generates 0.12 million tons of pond fish (carp) from 0.25 million hectares (ha) pond area, with an average annual yield of $\leq$0.5 tons ha^{-1}. The current use of cereals as traditional supplementary feeding (FCR 2.5–3.0) means using direct human feed-food conflict feedstuff in amounts of 0.3 million tons year^{-1}.
2. Future ecological pond aquaculture with 250–300 kg ha^{-1} fish stocking and fed with balanced pond feeds in harmony with the natural food web could easily generate $\geq$1 ton ha^{-1} fish yields (BioRural Toolkit; hyperlink). This means ~0.25 million tons of pond fish can be obtained 'ecologically' from CEER fishponds (0.25 million ha).
3. FCR of balanced pond feeds (~2) made up of LOCBs would be lower than cereals (FCR 2.5–3), meaning $\geq$50% less organic matter input and producing more fish with less feed use.

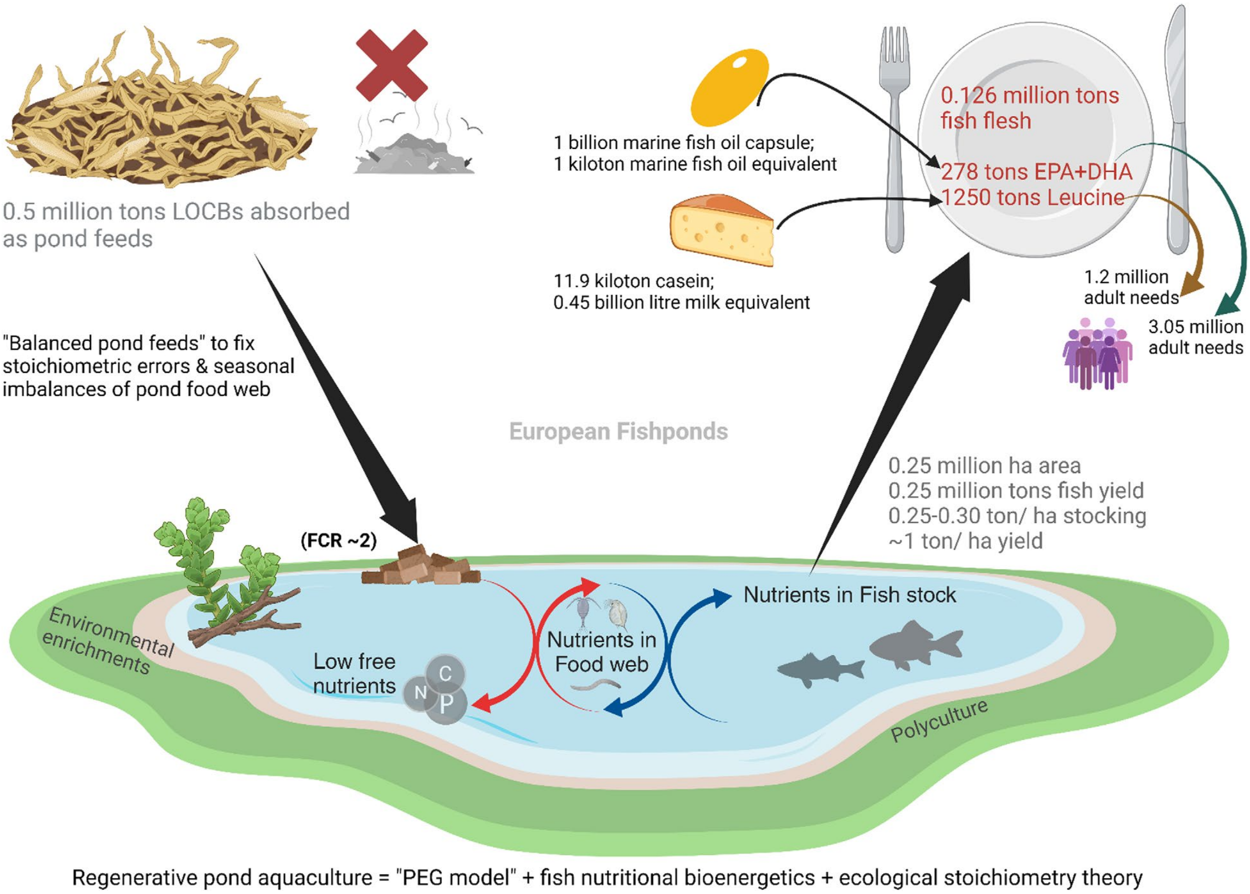

FIGURE 3 | A mind map of the potential of ecological pond aquaculture in European inland waters to fix food system problems and respect water protection. PEG model (plankton ecology group model [161]), ecological stoichiometry theory [162], and environmental enrichment [163] are standard terminologies in aquatic ecology, with potential use in pond aquaculture. LOCB (low-opportunity-cost biomass) is used in food system science [21].

4. 0.25 million ton pond fish yield would help absorb 0.5 million tons LOCBs via balanced pond feeds (FCR ~2). Thus, drawing down planetary health boundaries transgressions locally.
5. Considering 50% edible yield (500 g fillets + ground flesh per kg whole fish), ~0.12 million tons year^{-1} of human edible fish can be extracted from 0.25 ha CEER ponds.
6. Leucine is the limiting amino acid for human muscle synthesis, while EPA + DHA is a limiting fatty acid(s) for human brain development. Considering their achievable concentrations in pond carp by balanced pond feeding (0.22% EPA + DHA, 1% leucine), ~278 tons EPA + DHA year^{-1} and ~1250 tons leucine year^{-1} can be produced from CEER fishponds.
7. Assuming 91.25 g capita^{-1} annum^{-1} EPA + DHA requirement (250 mg EPA + DHA day^{-1}) and 1.02 kg capita^{-1} annum^{-1} leucine requirement (2.8 g leucine day^{-1}), CEER fishponds can singlehandedly fulfill annual demand of 3.05 million (EPA + DHA) or 1.2 million (leucine) adults.1.
8. It is equivalent to sparing 1 billion marine fish oil capsules (260 mg EPA + DHA capsule^{-1}) or 1 kt marine fish oil equivalent. It is equivalent to sparing 11.9 kt of casein (105 g leucine kg^{-1} casein) from 0.45 billion liters of milk (26.5 g casein l^{-1} milk).

See Figure 3 for the potential of CEER fishponds alone to provide limiting nutrients for land-locked European populations and relieve stress on 'overexploited' conventional sources (marine fishery or dairy). Some considerations, although reasonable, will require a careful assessment of feasibility. The study provides evidence and justification for their consideration in the future.

Author Contributions

Koushik Roy: conceptualization, investigation, methodology, formal analysis, visualization, writing – original draft, writing – review and editing, data curation. **Marc C. J. Verdegem:** writing – review and editing, validation, resources, supervision, writing – original draft. **Jan Mraz:** writing – review and editing, funding acquisition, project administration, resources, supervision, validation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.