Industry note: Closing the loop: integrated urban waste-to-aquaculture systems for enhanced resource efficiency and sustainability

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1 Introduction

The rising demand for seafood, coupled with the limitations of open ocean aquaculture, creates an urgent need for innovative and sustainable production systems (FAO, 2022). Cities, traditionally seen as resource sinks, hold untapped potential for food production within a circular economy framework (EEA, 2020). Organic urban waste streams contain valuable nutrients and energy resources that can be harnessed for aquaculture operations (Junge et al., 2017). This mismatch, along with the environmental impact of transporting seafood long distances (Macrea et al., 2015), highlights the urgency for localised, sustainable aquaculture models that transform waste into a resource. This paper explores the scientific and technological considerations for designing closed-loop urban waste-to-aquaculture systems, emphasising nutrient cycling, pathogen control, and the need for solutions tailored to the urban context.

> "There is no waste, only misplaced resources".

2 Nutrient cycling and system design

Closing the nutrient loop requires careful integration of multiple production systems. While aquaponics, linking fish and plant production, is a starting point, true circularity demands a more complex approach:

1. *Multi-species systems*: To maximise resource efficiency and create multiple revenue streams, incorporate shellfish varieties (e.g., oysters, clams, mussels) as natural biofilters that improve water quality, reducing reliance on costly engineered systems. These shellfish themselves become valuable food products (Neori et al., 2004). Additionally, integrate herbivorous fish species (e.g., tilapia, carp, milkfish or pangasius, depending on salinity and regional suitability) to directly consume excess algae or plant matter within the system (Rakocy et al., 2004; Martínez-Espinosa, 2022). This multi-species approach not only increases total productivity but also creates a resilient ecosystem where each species' waste products become a resource for another, minimising the need for external inputs and fostering self-sufficiency (Neori et al., 2004).
2. *Black soldier fly (BSF) integration*: BSF larvae play a critical role in urban waste-to-aquaculture systems, acting as efficient bioconverters that transform a wide range of food scraps (fruit and vegetable waste, bakery products, etc.) into nutrient-rich biomass for fish feed and a valuable organic fertiliser (Cai et al., 2017). Pre-treatment methods, such as fermentation or the use of targeted microbial inoculants, can further optimise this process. Fermentation breaks down complex organic molecules into simpler sugars and organic acids, making them more readily digestible by BSF larvae, ultimately increasing protein content and overall biomass production (Yi et al., 2019). Similarly, strategic inoculation with specific bacterial or fungal strains can enhance the nutritional profile of the BSF frass (excrement) – the final fertiliser product – by enriching it with beneficial microbes and micronutrients, promoting plant growth and soil health in aquaponic gardens (Wang et al., 2021). By combining BSF's natural bioconversion abilities with targeted pre-treatment strategies, waste-to-aquaculture systems can achieve maximised resource recovery and create a truly circular bioeconomy within urban environments.
3. *Microalgae as the powerhouse*: Microalgae hold immense potential as the foundation of urban waste-to-aquaculture systems. By carefully selecting specialised strains suited to the specific waste stream inputs, high-value nutrients, and bioactive compounds can be produced (Surendra et al., 2018). Innovative bioreactor designs, such as light-diffusing systems for optimal light penetration, and flow-through systems for continuous nutrient replenishment, can maximise the productivity of these microscopic powerhouses (Richmond, 2003). Urban waste streams can become the raw material for algae biomass, which can be directly used as fish feed or processed further to extract high-value omega-3 fatty acids, pigments, or antioxidants for the nutraceutical industry (Brennan and Owende, 2010; Pulz and

Gross, 2004). This creates a multi-tiered system where algae cultivation not only drives the aquaculture component but also generates additional revenue streams, increasing the economic viability of the entire model.

4 *Cascading use of resources*: True circularity within urban waste-to-aquaculture systems demands a focus on maximising value extraction from EACH waste stream. This creates a multi-level network of interconnected processes. Consider the example of coffee grounds: first, they become a nutrient-rich substrate for BSF larvae (Surendra et al., 2018). Next, the insect frass (excrement) serves as a potent organic fertiliser for aquaponic beds or traditional soil-based gardens (Cifuentes et al., 2021). Finally, any residual organic matter from the BSF process can be used as feedstock for microalgae cultivation. The algae, in turn, can yield biomass for biofuel or aquaculture feed, highlighting the potential for both food and energy production within this integrated system (Chisti, 2007). This cascading approach, where the output of one stage becomes the input for another, embodies the essence of regenerative urban resource management.

5 *Seaweed for added resilience*: Coastal urban waste-to-aquaculture systems can gain an additional layer of resilience and productivity by incorporating macroalgae (seaweed) cultivation. Seaweed offers natural biofiltration, improving water quality and reducing the burden on engineered systems (Chung et al., 2014). Moreover, as a fast-growing organism, seaweed acts as a significant carbon sink, helping to mitigate climate change impacts (Krause-Jensen and Duarte, 2016). Importantly, seaweed biomass has a multitude of high-value applications. It can be a direct source of nutritious food products, a base for valuable extracts used in cosmetics and nutraceuticals, or potentially even processed into bioplastics (Kraan, 2013). This potential for both ecological services and economic diversification strengthens the viability of coastal urban aquaculture models.

3 Wastewater: risks and technological solutions

Urban wastewater contains valuable nutrients but poses risks due to pathogens, heavy metals, and pharmaceutical residues. Robust pre-treatment is essential for direct use in aquaculture:

1 *Targeted filtration*: Robust pre-treatment of urban wastewater is essential for its safe and effective use in aquaculture. A multi-tiered approach, combining proven technologies like membrane filtration (particularly reverse osmosis for the removal of salts, heavy metals, and micropollutants), and activated carbon (effective in absorbing organic contaminants and pesticides), offers effective initial treatment (Tang et al., 2018). Complementing this with biofiltration, where specialised bacterial biofilms develop on tailored substrates, can further degrade specific contaminants of concern, such as pharmaceuticals or antibiotic residues (Li and Zhang, 2019). This adaptable, multi-stage approach prioritises the removal of the critical contaminants identified in the specific urban waste stream, ensuring the safety of the final water output for the aquaculture system.

2 *Microbe-assisted treatment*: Addressing persistent contaminants in urban wastewater, such as micropollutants (pharmaceutical residues, microplastics) and

heavy metals, requires innovative approaches. Emerging research focuses on harnessing the power of specialised microbial consortia – diverse communities of bacteria, fungi, and other microbes that work together to achieve complex tasks (Khan et al., 2020). These consortia can naturally develop within biofilms, where they break down stubborn pollutants or sequester (trap) heavy metals, rendering them less harmful (Imfeld and Vuilleumier, 2012). By carefully selecting and potentially enriching specific microbial communities within engineered environments, tailored microbe-assisted treatment could become a powerful tool for safe utilisation of urban wastewater, particularly in space-constrained settings where more traditional treatment methods may be less feasible.

3 *Real-time monitoring*: Closed-loop urban waste-to-aquaculture systems demand rigorous, real-time monitoring to ensure system safety, optimise production, and enable quick interventions when needed. Integrate sensors that continuously monitor key water quality parameters such as ammonia, nitrite, nitrate, salinity, pH, dissolved oxygen, and temperature (Lefevre et al., 2013). Complement these with rapid assays, like environmental DNA (eDNA) detection, which allow for early identification of potential pathogens or harmful algal blooms before they become problematic (Janeiro et al., 2021). Data from these sensors, when integrated with automated alerts and potential adjustments to treatment processes, create a responsive system. This minimises risks and fosters a proactive approach to system management, vital when resources are tightly interconnected with urban centres.

4 *Beyond traditional water parameters*: The presence of emerging contaminants like microplastics and persistent pharmaceutical residues poses unique challenges in urban wastewater treatment. Investigating extremophile bacteria, organisms thriving in seemingly hostile environments like high pH, low oxygen, or high salinity, opens new possibilities (Danso et al., 2019). These specialised bacteria and their consortia may hold the key to developing biological pre-treatment steps. Research suggests the potential for these extremophiles to degrade specific types of microplastics or break down pharmaceutical compounds that traditional treatment systems struggle to remove (Auta et al., 2017; Roh et al., 2021). Harnessing the metabolic capabilities of extremophiles for the pre-treatment of urban wastewater could transform seemingly unusable waste streams into safe and productive inputs for aquaculture.

4 Space, scalability, and the urban context

Urban space is limited and expensive. This model demands solutions that maximise productivity per square meter:

1 *Vertical and modular design*: Urban space constraints necessitate a design approach that prioritises maximising output per square meter. Modular, stackable aquaponic systems that optimise vertical space are crucial (Thomaier et al., 2015). Explore the potential of rooftop farms and vertical green walls, transforming otherwise unused surfaces into productive food systems. Additionally, repurposing existing urban infrastructure, such as vacant warehouses or underutilised industrial spaces, can unlock valuable growing areas within the city (Orsini et al., 2020). By emphasising a

modular approach, systems can be scaled up or down as needed, allowing the model to adapt to diverse urban landscapes and evolving needs.

2 *Micro-scale and distributed approach*: Large-scale, centralised urban waste-to-aquaculture systems may not always be the most feasible or desirable solution. Investigate the potential of a micro-scale and distributed approach, where waste conversion and food production happen at the neighbourhood level. This can involve establishing neighbourhood-level BSF facilities that process local food scraps (Lalander et al., 2019). Similarly, explore utilising compact bioreactors for microalgae cultivation or modular, 'plug-and-play' aquaponic systems that can be easily integrated into homes, restaurants, or schools. This distributed approach offers several advantages. It reduces transportation needs for organic waste materials, fostering a more localised circular economy within each community. Additionally, smaller, neighbourhood-scale systems can be more easily managed and tailored to meet specific needs, potentially fostering a stronger sense of community ownership and buy-in for this innovative food production approach.

3 *Beyond food, towards zero-waste*: A true circular economy approach means finding value in every output of the urban waste-to-aquaculture system. Excess plant parts from aquaponics beds, non-edible fish, or shellfish by-products, and even chitin shells from the BSF larvae can all find new purposes. These organic materials can become feedstock for small-scale biogas production, generating localised energy to power aspects of the system (Surendra et al., 2018). Furthermore, emerging research explores the potential of transforming this waste biomass into bioplastics, creating a closed-loop packaging solution tailored to the 'upcycled' products generated within the city (Cingolani et al., 2022). This demonstrates how even the seemingly minor outputs of the system can be reintegrated, minimising waste, and driving towards true sustainability.

4 *Redefining 'urban'*: While focusing on waste-to-aquaculture within dense city centres is essential, there's significant potential in exploring the model's application in peri-urban areas. These are the transitional zones surrounding smaller cities and towns, often with a mix of agricultural and urban development. Peri-urban hubs offer advantages like greater land availability at potentially lower costs, and a proximity to diverse waste sources (e.g., agricultural residue, food processing waste) (Little et al., 2002). Establishing urban waste-to-aquaculture systems in these areas also aligns with broader regional development goals. It can create much-needed economic revitalisation in 'in-between' areas. This approach encourages a wider view of urban-rural linkages, where cities are not merely resource sinks but also provide valuable inputs to agriculture in their surrounding regions – strengthening overall regional food security and resilience.

5 The 'X' factors: policy, economics, and public trust

1 *Navigating regulations*: Current regulatory frameworks, often designed for traditional agriculture or aquaculture practices, may not fully address the specificities of waste-derived food production. To unlock the full potential of urban waste-to-aquaculture systems, a collaborative effort is needed to develop tiered,

risk-based regulatory models. These models should consider the specific types of waste used, the treatment processes in place, and the final products being produced (fish, shellfish, microalgae) (Wolf et al., 2017). This tiered approach allows for efficient and proportionate risk management. Alongside regulatory adjustments, rigorous, transparent science on contaminant pathways and mitigation strategies is crucial. Open communication and collaboration between scientists, regulators, and industry stakeholders will be vital for developing robust safety measures and building public trust in this innovative approach to food production.

2 *The business case*: Thorough cost-benefit analyses are crucial for understanding the economic viability of urban waste-to-aquaculture systems. Such assessments must include upfront infrastructure investments, like specialised filtration technology and bioreactors, as well as potential long-term operational savings achieved by repurposing waste inputs that would otherwise need to be managed through traditional disposal. Emphasise the potential for high-value niche products, with their 'upcycled' urban origin becoming a unique selling point for discerning consumers (Grewal and Grewal, 2012). Critically, comparisons should be drawn not only to traditional aquaculture but also to existing urban composting models. This provides a holistic picture of the system's position relative to alternative waste management and food production pathways, highlighting its potential for economic competitiveness within a city's context.

3 *Changing mindsets*: Success of this model hinges on shifting public perception of food derived from urban waste. Providing robust data on safety measures, lifecycle impacts (e.g., reduced pollution, transport emissions), and the tangible benefits to existing urban waste management systems is essential. Alongside data, clever marketing that emphasises the 'upcycled' aspect and positions these foods as a sustainable, premium choice can attract early adopters (Ellen MacArthur Foundation, 2013). Implementing innovative traceability technology, such as blockchain solutions, increases transparency, allowing consumers to follow their food's journey from urban waste to their plate. Finally, active community engagement is vital. Workshops, open facility days, and collaborations with local food movements can foster dialogue, address concerns, and build public acceptance for a novel way of producing food within cities.

4 *Beyond regulations, towards incentives*: While regulatory frameworks are necessary for ensuring safety, cities can truly accelerate the adoption of urban waste-to-aquaculture systems by shifting the regulatory role from potential barrier to active catalyst. This involves offering various incentives for businesses and communities demonstrably building on this closed-loop model. Tax breaks, streamlined permitting processes for facilities conforming to the model's principles, and even guaranteed purchase agreements for locally produced seafood could make these systems highly attractive. Such policy measures create a positive feedback loop, fostering both investment and innovation in this sector. These cities not only reap the environmental benefits but also position themselves as leaders in circular economy solutions, attracting forward-thinking businesses and a sustainability-minded population.

5 *The economic lens*: Moving beyond individual projects, robust economic modelling tools can help us compare different scenarios for urban waste management and food production. Analyse a situation where a city focuses on a centralised waste-to-aquaculture system, compared to one promoting hyper-local composting in community gardens. Life cycle assessment (LCA) tools can be used to evaluate the environmental impact (e.g., reduced greenhouse gasses, water use) of each approach. Economic modelling can then examine the impact on transportation needs. In the centralised model, transportation costs might be higher for waste collection, while a hyper-local approach might see reduced overall movement of materials. Job creation within the waste management sector could also be analysed. The centralised model might require specialised personnel for operating the waste-to-aquaculture facility, while hyper-local composting might create opportunities for community garden coordinators or composting educators. Finally, consider the potential for distributed small businesses emerging within this new system. Both scenarios could see opportunities for niche businesses specialising in waste collection for hyper-local composting, or specialised fish feed production for the waste-to-aquaculture facilities. By comparing these scenarios, cities can make data-driven decisions that optimise the economic and environmental benefits of waste management, with the potential to create new jobs and foster a more vibrant and sustainable urban food system.

6 Call to action

This revolution requires collaboration across disciplines:

1 *Interdisciplinary teams*: The success of urban waste-to-aquaculture systems depends on the collaboration of experts from diverse disciplines. Waste management experts bring knowledge of waste stream composition, collection logistics, and pre-treatment technologies to ensure a consistent input supply (Singh et al., 2014). Aquaculture engineers design and optimise aquaponic systems, bioreactors, and water recirculation systems tailored to the specific waste-driven environment. Food scientists ensure the nutritional quality of end products, food safety throughout the process, and develop value-added products from by-products. Urban ecologists contribute their understanding of broader ecological impacts, nutrient cycling, and how these systems can be integrated into existing urban landscapes for maximum benefit. True integration occurs when these experts work together from the earliest planning stages. This goes beyond simply co-locating existing operations into a shared space. It’s about designing systems where each expert’s knowledge informs the choices for waste streams, technologies, species selection, and potential product lines, allowing this model to reach its full potential.

2 *Pilot projects and data sharing*: The true potential of urban waste-to-aquaculture systems will be unlocked through a network of pilot projects implemented in diverse urban settings. These projects serve several crucial purposes. Firstly, they act as real-world testing grounds for innovative solutions, allowing researchers and practitioners to refine technologies and identify any unforeseen challenges specific to local contexts. Secondly, pilot projects generate valuable, real-world data on factors like system efficiency, water quality parameters, and final product yields (Genest

et al., 2019). This data becomes the foundation for informing best practices, designing future iterations of the system, and ultimately, building a robust case for regulatory change. To accelerate innovation and knowledge sharing, open-source databases could be established for pilot project data, along with the development of open-source modelling tools. These would allow researchers in different cities to learn from each other's successes and challenges, fostering a collaborative spirit that pushes the boundaries of this transformative approach to urban food production and waste management.

3 *Research gaps*: While significant progress has been made, targeted research is essential to unlocking the full potential of urban waste-to-aquaculture systems. Several key areas require focus:

   a *Optimising waste streams*: More in-depth research is needed to determine how best to utilise specific urban waste streams (e.g., restaurant food scraps, agricultural residues, market waste) as inputs for aquaculture. This includes

      - Understanding the nutritional profile of different waste sources. Urban waste streams are not 'one-size-fits-all.' Research needs to characterise the nutritional makeup (proteins, fats, carbohydrates, micronutrients) of different waste sources and how they change seasonally or with different generators (e.g., restaurants vs. food processing facilities) (Su et al., 2021; Elhenawy et al., 2024).
      - Explore the effect of pre-treatments like fermentation, enzymatic hydrolysis, or targeted microbial enrichment on making waste streams more digestible and improving their nutritional value for fish or shellfish (Pecoraro et al., 2022).
      - Identify fish, shellfish, and plant species particularly well-suited to thrive on specific waste streams after pre-treatment. Investigate the potential of less traditional aquaculture species that might excel in these unique environments (Gasco et al., 2016).

   b *Long-term impacts*: Research into the long-term social and economic impacts of this model is essential. This includes:

      - Quantify potential jobs not just within the aquaculture facility but also in upstream waste collection, pre-treatment, transportation, and value-added processing of by-products. Consider the potential for new specialised job categories (Skarmeas and Leontides, 2013).
      - Model how these systems could impact existing municipal waste management costs by reducing landfill or incineration volumes. Analyse if a city's cost savings can be reinvested as incentives to accelerate adoption of this model (Geng et al., 2019).
      - Study the impact on surrounding communities -potential concerns (e.g., odours, perceived safety) as well as benefits like increased food access, green spaces, or educational opportunities (Orsini et al., 2020).

   c *Pathogen control in closed systems*: Developing reliable, efficient, and cost-effective pathogen control technologies tailored to closed-loop urban aquaculture is crucial for ensuring food safety. This includes:

- Research how the pre-treatment technologies (filtration, bioreactors, etc.) can remove both traditional biological pathogens and contaminants specific to urban wastewater (pharmaceuticals, microplastics) (Khan et al., 2020).
- Explore how engineered microbial consortia could be targeted towards the specific pathogens likely to be prevalent in urban waste streams before they reach the aquaculture tanks (Ma et al., 2021).
- Investigate the combination of continuous parameter monitoring (pH, temperature, etc.) with rapid assays like eDNA (environmental DNA) detection to identify outbreaks early. This can prevent widespread contamination within the closed-loop system (Janeiro et al., 2021).

4. *Global testbeds needed*: Integrated urban waste-to-aquaculture systems offer a tantalising solution for boosting sustainable food production within cities. However, their applicability and challenges vary greatly depending on the specific urban context. Here is a glimpse into how Vietnam, Indonesia, and India, with their diverse landscapes and waste profiles, could leverage and confront the complexities of this model:

   a. *Vietnam*: Land of paddy fields and concentrated cities
      - *Applicability*: Vietnam boasts a flourishing agricultural sector generating abundant rice straw, a potential source of cellulose for BSF larvae. Its dense urban centres, particularly Hanoi and Ho Chi Minh City, create a ready market for locally produced seafood. Existing freshwater aquaculture provides a base for technical knowledge and infrastructure.
      - *Challenges*: Integrating waste streams with existing aquaculture requires investment in infrastructure and training. Public education will be crucial to overcome potential concerns about using treated wastewater in food production.

   b. *Indonesia*: Island nation with growing urban woes
      - Applicability: Indonesia’s massive population centres, like Jakarta and Surabaya, struggle with organic waste management. The established aquaculture sector, particularly for shrimp and seaweed, could readily integrate with waste-to-aquaculture systems. Government initiatives promoting the ‘Blue Economy’ align well with the model’s circularity principles.
      - Challenges: Coordinating waste collection across sprawling urban landscapes can be a hurdle. Developing cost-effective, scalable systems suited to the Indonesian context is crucial. Stringent regulatory frameworks for food safety need to be addressed.

   c. *India*: Diverse waste streams and high demand
      - *Applicability*: India’s densely populated cities like Delhi and Mumbai face significant food waste management challenges. The diverse waste streams, including food scraps, agricultural residues, and livestock manure, offer a variety of potential inputs. The rapidly growing aquaculture sector provides fertile ground for integration.

- *Challenges*: India’s complex social and economic landscape can pose challenges in implementing uniform waste collection and treatment systems. Research is needed to optimise waste streams specific to different regions within India.

d *Singapore*: The tech-savvy city-state embraces innovation

- *Applicability*: Singapore government commitment to food security (‘30 by 30’ initiative) drives a search for innovative solutions. High population density reduces transportation needs, making local seafood attractive. A focus on R&D can lead to cutting-edge solutions for space-efficient systems and advanced waste treatment. The affluent population’s willingness to pay a premium for ‘sustainable’ or ‘local’ products aligns with the model’s niche market potential.
- *Challenges*: Extremely limited land necessitates intensive, vertical, and technologically advanced systems. Competition for clean organic waste streams with existing waste-to-energy infrastructure exists. Strict regulations on food safety and wastewater reuse necessitate exceeding standard industry practices to ensure public trust.

These examples showcase the adaptability of waste-to-aquaculture systems. Vietnam might utilise rice straw and integrate with existing practices, while Indonesia might prioritise scalability across vast urban areas. India requires region-specific solutions for diverse waste streams, and Singapore focuses on maximising output per square meter through advanced technology.

7 Conclusions

Integrated urban waste-to-aquaculture systems offer a compelling, though complex, solution for sustainably increasing food production within cities. While not intended as a sole replacement for traditional aquaculture, these systems demonstrate significant potential to enhance urban resilience, reduce the environmental impact of seafood production, and promote a more circular approach to resource management. This model highlights the intersection of human ingenuity with ecological principles, emphasising the importance of closed-loop systems for sustainable urban development. By effectively harnessing the latent value in urban waste streams, cities can transition from resource sinks to regenerative hubs of food production, redefining their role in the global food system, where resources are valued, and waste is repurposed. Further research into optimising these integrated systems and addressing the complexities inherent in their implementation is crucial for unlocking their full potential towards more sustainable and resilient cities.

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