The evolution of technological knowledge in the Global Value Chain (GVC) of mixed-tech industries: An explorative study of European aquaculture.

In Global Value Chains (GVCs), technological knowledge is typically generated and governed by countries in core positions in the global economy, particularly advanced industrialized economies, hosting multinational enterprises and lead firms coordinating high-value-added activities such as R&D, design, and intellectual property management. This concentration reflects strong national innovation systems, cumulative technological capabilities, and sustained public-private R&D investments (Antrás & Chor, 2022; Coe & Yeung, 2015; Fernandez-Stark & Gereffi, 2019). As a result, technological capabilities are unevenly distributed, while peripheral or semi-peripheral economies often participate in lower value-added functions such as assembly, processing, and standardized production. Upgrading requires deliberate capability building and access to knowledge networks (Lema et al., 2019; Pietrobelli et al., 2021; Taglioni & Winkler, 2016; Wang et al., 2021).

Recent literature on mixed-technology GVCs shows that high- and low-tech segments frequently co-exist within the same value chain, producing asymmetric knowledge flows shaped by power hierarchies and institutional contexts (Gereffi, 2019; Morrison et al., 2008). From an evolutionary geography perspective (Boschma, 2022, 2024), such asymmetries are not static: they evolve through processes of path dependence, related diversification, and knowledge recombination. Crucially, interregional collaboration and extra-local knowledge pipelines can enable new entrants to reposition themselves within GVCs, especially during periods of structural transition.

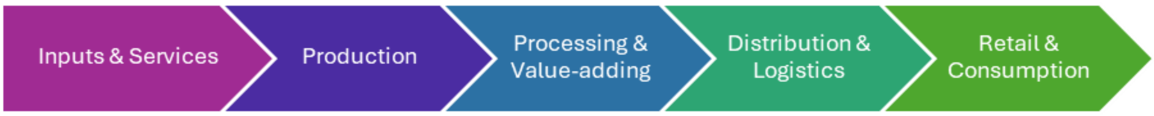
The aquaculture GVC offers a compelling case. Technological leadership is concentrated in a limited set of countries, including Norway, Scotland, Denmark, Canada, and Chile, particularly in upstream segments such as breeding and genetic improvement, feed innovation, digital motoring systems, and disease management (Asche et al., 2015; Bergesen & Tveterås, 2019; Nielsen et al., 2025). These countries combine vertically integrated firms, strong research institutions, and coordinated public-private innovation systems. In contrast, may Southern and Eastern European regions, as well as Asian producers, focus more heavily on grow-out farming and processing activities, with more fragmented innovation systems and smaller firms structures (Bush et al., 2019). These countries often have limited access to or control over innovation-intensive segments, thereby reinforcing structural asymmetries in technological knowledge within mixed-tech GVCs (Boschma, 2022; Lema et al., 2019).

Within Europe, the geography of technological innovation in aquaculture is equally uneven. Northern and Western European regions, notably Norway, Scotland, and Denmark, hold a technological leadership position, driven by innovation in closed containment systems, smart feeding technologies, and environmental control for salmon farming (Asche et al., 2015; Boschma, 2024; Bush et al., 2019; Tsakanikas et al., 2022). These regions benefit from global export orientation and concentrated knowledge systems, while regions in Southern and Eastern Europe, including Greece, Italy, and Bulgaria, focus on Mediterranean species such as sea bass and sea bream, often within less integrated and fragmented value chains (EUMOFA, 2023; Torrissen et al., 2011). Although there is evidence of increasing technological adoption, especially in sustainable feed production and disease resistance, innovation diffusion remains limited due to structural constraints like smaller firm size and lower R&D intensity (European_Commission, 2021). These patterns point to a fragmented and multi-scalar innovation system, where knowledge creation is localized but not equally accessible. In light of these dynamics, a pressing research question emerges: **How does green and digital transition affect the geography of the technological knowledge and the evolution of mixed-tech industries' GVCs like aquaculture industry? What mechanisms enable or hinder functional upgrading across different geographic regions?**

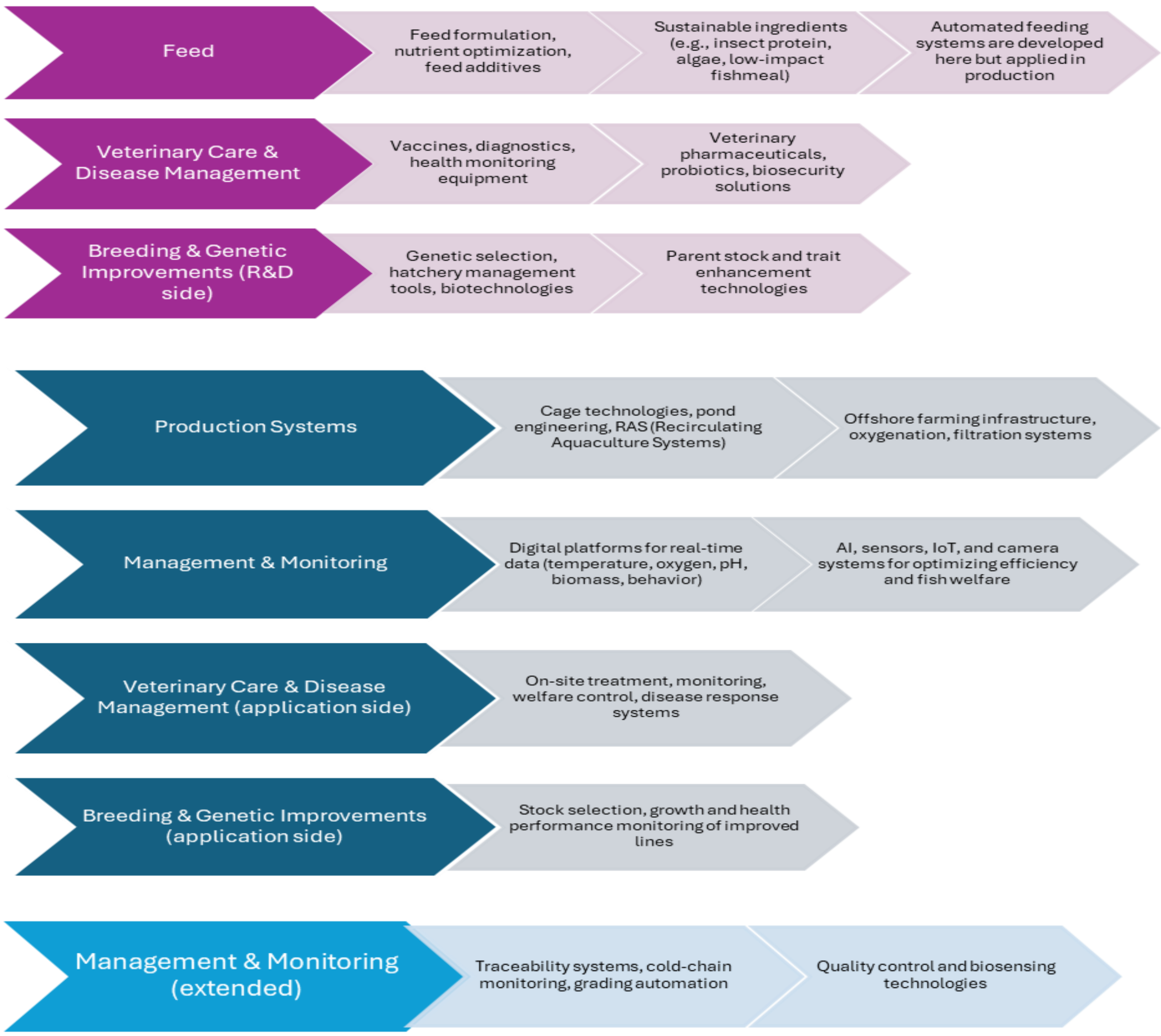
To address these questions we collected patent data on related to aquaculture industry with at least one inventor located in a European country (European Union, United Kingdom, Norway, Iceland and Switzerland) for the period 2000-2024. We divided the period in five non overlapping consecutive periods (2000-2004, 2005-2009, 2010-2014, 2015-2019, 2020-2024). We have attributed each Cooperative Patent Code (CPC) into five technological foci (*Feed*, *Production system*, *Management and monitoring*, *Veterinary care and disease management*, *Breeding and genetic improvements*) as shown to Table 1 below. Multiple categories can be listed for each CPC as multiple CPC codes can be assigned to one patent.

Focus	**CPCs**
Feed	A01K 61/80; A01K 61/85; A23K 50/80; Y02A40/818; A23K 10/00
Production system	A01K 61/00; A01K 61/10; A01K 61/17; A01K 61/30; A01K 61/50; A01K 61/51; A01K 61/53; A01K 61/54; A01K 61/55; A01K 61/56; A01K 61/57; A01K 61/59; A01K 61/60; A01K 61/65; A01K 63/00; A01K 63/02; A01G 33/00; A01K 63/04; A01K 63/042; A01K 63/045; A01K 63/047; A01K 63/06; A01K 63/10; Y02P60/21; A01K 61/70; A01K 61/72; A01K 61/73; A01K 61/75; A01K 61/77; A01K 61/78; B63B 35/00; C02F 1/00; C02F 3/00; C02F2103/023; C02F2103/20; C02F2103/025; Y02W10/00; Y02W10/10; Y02W10/30; Y02W10/40
Management and monitoring	A01K 61/90; A01K 61/95; Y02A40/80; Y02A40/81; Y02P60/60; G08C 17/02; G01N 21/00; G06Q 50/02; G01S 15/96; G01N 33/18; B25J 19/02; G06N 20/00
Veterinary care and disease management	A01K 61/13
Breeding and genetic improvements	A01K67/32; A01K67/62; A01K67/67; C12N 5/00

Apart from the different technological foci, incremental value is added to the product in the successive nodes of a value chain either by value addition or value creation (Ababouch et al., 2023). Similarly, technological knowledge may add value to the innovation resulting in each segment of the value chain (Buciuni & Pisano, 2021; Fernandes et al., 2022; Tsakanikas et al., 2022). Therefore, tracing the geography of the technological knowledge in the aquaculture industry, it is possible to trace the GVC of innovation in an industry, in our case aquaculture. Following recent literature by Bush et al. (2019) and Ababouch et al. (2023), we have been able to draw the value chain of aquaculture as shown in Figure 1 below. We attributed the patent CPCs to each segment of the value chain, and as expected their vast majority were attributed to upstream segments of the value chain which are more technologically intensive, while downstream the value chain can be attributed technological knowledge that may belong to the general category of fisheries.



Then we attributed according to the technologies represented by CPCs, the five technological foci to each one of the first three sections of aquaculture GVC, creating in this way three sub-value chains: Inputs & Services (Figure 2a), Production (Figure 2b), and Processing & Value-adding (Figure 2c). The different elements of the five technological foci can belong to more than one value chain segment.



To map both global and European perspectives of the knowledge used in the five technological foci attributed to the three first segments of the aquaculture value chain, we used country and region level square matrices and Social Network Analysis techniques for each time period in focus. For each focus and value chain segment, we created descriptive knowledge networks which can trace the spatial evolution in the global and European scale of the technological knowledge in each value chain segment under focus. Although, the research is in early stage, preliminary results indicate the participation of new entries countries and regions to the European aquaculture knowledge creation, especially as the knowledge progresses in more green trajectories.

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