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Application of the food-energy-water nexus to six seafood supply chains: hearing from wild and farmed seafood supply chain actors in the United States, Norway, and Vietnam

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Introduction: The food-energy-water (FEW) nexus highlights the interdependencies between the systems that people rely on for these essential resources. For example, globally, over two thirds of freshwater withdrawals are used to produce food, and another 10% is used during energy generation. In addition, the food system uses one eighth of global net energy. Seafood is a nutritionally important food, and it is critical to use freshwater and energy resources efficiently throughout seafood supply chains to safeguard future supplies and to reduce environmental impacts. Diverse seafood production methods result in highly variable resource use across supply chains, which may contribute to siloed efforts within supply chains to improve efficiency, instead of larger efforts that involve multiple seafood supply chains. Additionally, efforts to develop and implement efficiency strategies must be informed by fishers, aquaculturists, processors, and other seafood supply chain actors to avoid investing time and resources into strategies that will have low uptake. A significant proportion of seafood is imported into the U.S., so engaging with industry and stakeholders in the U.S. and abroad is critical for understanding and improving the FEW nexus associated with seafood consumed by Americans.

Methods: To understand how resources are being used, current and potential strategies to improve resource use, and relevant motivations and barriers, we conducted 47 semi-structured interviews from 2019 to 2021 with seafood supply chain actors, including producers and processors. Seafood supply chains included were farmed catfish produced in the U.S., farmed pangasius and shrimp produced in Vietnam, farmed Atlantic salmon produced in Norway, and wild-caught sockeye and pink salmon caught in the U.S.

Results: We provide detailed descriptions of stages within each supply chain regarding resource use and efficiency strategies, and report higher-level findings that apply across supply chains. There was variation across settings regarding how resources are used and opportunities and barriers for improving efficiencies, but we also found commonalities in settings, indicating that resource-saving strategies or innovations could lead to increased efficiency across multiple supply chains. Interviewees shared that cost savings drove past adoption of, and high interest in, energy conservation practices. Generally, direct costs did not motivate reduced use of freshwater, but associated costs like energy to run pumps and supplies to treat contaminated surface water drove interest in reducing water use.

Discussion: Efforts to improve resource use in the U.S. seafood supply should focus on identifying and scaling-up strategies that (i) involve improved efficiency of more than one resource and/or (ii) apply across multiple settings. This work should involve partnerships between industry, government agencies, and academic researchers, and should be informed by supply chain actors' experiences and insights. The qualitative insights from this study encompass rich descriptions of FEW-relevant factors at the level of specific supply chain stages as well as findings across six major seafood supply chains in three countries. The study provides an essential complement to existing quantitative characterizations of resource use, and enables nuanced and informed responses to challenges.

KEYWORDS

seafood, sustainability, food-energy-water nexus, food system, fisheries, aquaculture

1 Introduction

Supplying a nutrient-rich diet to a growing population without damaging the environment is a significant global challenge, and seafood plays an important role (Gordon et al., 2017; Troell et al., 2019; Fanzo et al., 2021; Naylor et al., 2023). According to the Food and Agricultural Organization of the United Nations (FAO), at least 767 million people lacked access to nutritious food in 2021, the equivalent of one out of every nine persons. Seafood, also called aquatic food (i.e., edible fish, shellfish, and crustaceans from fresh, brackish, or seawater), is an excellent source of protein, omega-3 fatty acids, and vitamins and minerals essential for good health (FAO, 2022). For 3.3 billion people, seafood provides at least a fifth of their animal protein intake (Golden et al., 2021; FAO, 2022). Seafood can reduce malnutrition and food insecurity, generally with an equivalent or lower environmental footprint than most terrestrial animal-based food sources (Gephart et al., 2021; Golden et al., 2021).

The food, energy, and water (FEW) nexus considers the interconnectedness of these three critical necessities and their dependence on one another (Albrecht et al., 2018; Abdi et al., 2020; Proctor et al., 2021). The nexus approach seeks to understand the tradeoffs within each resource while optimizing their synergies (Scanlon et al., 2017; Abdi et al., 2020). The interdependencies in the FEW nexus at the global level are striking. For example, 69% of freshwater withdrawals are used in the food production stage of the food system, including for irrigation, livestock, and aquaculture (UNESCO World Water Assessment Programme, 2021), and 10% of global withdrawals are used for energy (International Energy Agency, 2023). More than half (57%) of the water used in the global energy system is used to produce, process, and transport fossil fuels or during fossil fuel-powered electricity generation (International Energy Agency, 2023). The food system, including all stages from food production to retail and households, is estimated to be responsible for 13% of global net energy use (Usubiaga-Liaño et al., 2020). In North America, the following stages/uses comprise 75% of net energy use in the food system: agriculture (17%), food processing (19%), electricity/heat (19%), transport (4%), and households (16%; Usubiaga-Liaño et al., 2020). These are just a few high-level examples of the interdependencies in the FEW nexus.

Facilitating improvements in the FEW nexus requires the engagement of stakeholders whose actions define their status (Ghodsvali et al., 2019), but the integration of stakeholders in FEW nexus work is limited, except as end-users of the results (Hoolohan et al., 2018). The multifaceted nature of the FEW nexus requires multidisciplinary collaboration to effectively address system complexities (Bergendahl et al., 2018; Hoolohan et al., 2018; Ghodsvali et al., 2019), and qualitative research with stakeholders can provide critical insights on drivers and barriers that complement quantitative approaches (Bergendahl et al., 2018; Yung et al., 2019; Kropf et al., 2021). For example, comprehensive stakeholder engagement is an important element of marine spatial planning, as it is recognized that the long-term success of fisheries management demands consideration of human activities and ecological resources in decision-making (Pomeroy and Douvere, 2008; Nutters and Pinto da Silva, 2012). Most research to date on FEW nexus systems has focused on approaches that consider the nexus from a technological lens (Daher et al., 2017; Bergendahl et al., 2018; van Gevelt, 2020). Therefore, multidisciplinary knowledge informed by stakeholders who are connected to or impacted by FEW nexus realities is needed (Hoolohan et al., 2018; Yung et al., 2019; Kropf et al., 2021).

Multiple factors affect resource use in seafood production, with varying potential for adaptation. In capture fisheries, direct use of fuel and indirect inputs such as water are required to produce the fossil fuel energy to operate fishing vessels (Troell et al., 2019; Liu et al., 2020; Viglia et al., 2022a). In addition to being an indicator of environmentally unsustainable practices, the high reliance on fossil fuels has exposed fishery sectors to rising fuel costs and fuel price fluctuations that have challenged the viability of some fisheries (Parker et al., 2018). Aquaculture also relies heavily on fossil fuels, but aquaculture has a greater opportunity to shift to clean, renewable sources because electricity from major utilities comprises a significant share of energy used (Scroggins et al., 2022). At the same time, some forms of aquaculture are dependent on capture fisheries as a source of marine ingredients for fish feeds.

Technological innovations have enabled intensification of aquaculture (Asche et al., 2022) which results in greater yields per unit cost and provides economies of scale (Kumar et al., 2020). However, it has also resulted in more water and energy use to provide feed, exchange water, and maintain water quality during production (Wilfart et al., 2013; Viglia et al., 2022b). In addition, processing of seafood has become more automated in some sectors (Asche et al., 2018), and thus energy and water demands have changed (Brown et al., 2022). Seafood production and processing methods are highly variable within both aquaculture and wild-capture fisheries (Naylor et al., 2021) and also vary significantly by species (Love et al., 2022), resulting in heterogeneous resource use profiles and environmental impacts, and bidirectional interactions between fisheries and aquaculture (Natale et al., 2013; Troell et al., 2019; Bohnes and Laurent, 2021).

The United States (US) sources seafood from all over the world and is the world's leading importer of seafood by value and second in terms of quantity (Shamshak et al., 2019). Over the last thirty years, the US seafood supply has consistently delivered ~5.8 oz. per person weekly (National Marine Fisheries Service (NMFS), 2022). This is largely supplied from imports, and increasingly from aquaculture, as US and global capture fisheries are fully exploited while aquaculture production is growing (Garlock et al., 2020). However, although there is significant variation between demographic groups, almost 90 percent of Americans do not meet US Department of Agriculture (USDA) dietary intake recommendations (U.S. Department of Agriculture and U.S. Department of Health and Human Services, 2020; Love et al., 2022, 34). Recommendations from US Department of Health and Human Services (HHS) and USDA to double seafood consumption among Americans raise sustainability concerns related to resource use (U.S. Department of Agriculture and U.S. Department of Health and Human Services, 2020). Resource inefficiencies, including waste of seafood, and increasing stress on resources due to changing global diets and climate change highlight the need for practical, cost-effective interventions to improve existing supply chain practices and resource use efficiency (Halpern et al., 2019; Love et al., 2020).

This paper contributes to an improved understanding of the FEW nexus and sustainable food systems, with a focus on seafood. In-depth exploration of seafood is essential due to its distinctive and variable production practices, long supply chains, perishability, and nutritional value. Studies on the FEW nexus and/or seafood sustainability tend to have a quantitative approach and many focus on one stage of a supply chain (e.g., fishing or farming) and/or one type of seafood. In addition, studies that cover multiple stages and/or supply chains often use secondary data from multiple sources (for example, see Hallström et al., 2019 and Koehn et al., 2022). This paper adds to, and complements, the existing literature by providing highly detailed descriptions of (i) how water and energy are used in production and processing stages across six seafood supply chains, (ii) how use of these resources has changed over time, and (iii) perspectives of supply chain actors on potential strategies to improve efficiencies. The results are based on primary data collected via qualitative interviews. The insights cover wild-caught, farmed, domestic (US), and international seafood supply chains, thus enabling analysis of synergies and tradeoffs regarding use of energy and water within and across seafood supply chains.

1.1 Seafood supply chains

This study focuses on four of the nine most consumed species groups in the US (Figure 1): shrimp, salmon, catfish and pangasius; and more specifically on six important supply chains: Vietnam farmed shrimp (*Penaeus monodon*, *Litopenaeus vannamei*), Vietnam farmed pangasius (*Pangasius hypophthalmus*); US farmed channel (*Ictalurus punctatus*) and hybrid (*I. punctatus* x *I. furcatus*) catfish; Norway farmed Atlantic salmon (*Salmo salar*); US Alaska wild capture sockeye salmon (*Oncorhynchus nerka*) and US Alaska wild capture pink salmon (*Oncorhynchus gorbuscha*).

1.1.1 United States Alaska wild sockeye salmon

The Alaska sockeye salmon fishery is one of the largest and most valuable sockeye fisheries in the world and is a major economic driver in rural Alaska. The fishery operates during a short 4–6-week period in the summer when sockeye salmon return from the ocean to spawn in the rivers that flow into Bristol Bay. The fishery uses two types of gillnets, driftnets and setnets (description of gillnets).[1] The fishery harvests an average of 96 thousand tonnes of sockeye annually, valued at $409 million USD (Alaska Department of Fish and Game (ADFG), 2022). Salmon is the second most consumed species group in the US, surpassed only by shrimp (Love et al., 2020). The short season also highlights the challenge of the industry in serving a market across an entire year, and contributes to the use of imported products (Love et al., 2023b).

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[1] https://www.fisheries.noaa.gov/national/bycatch/fishing-gear-gillnets

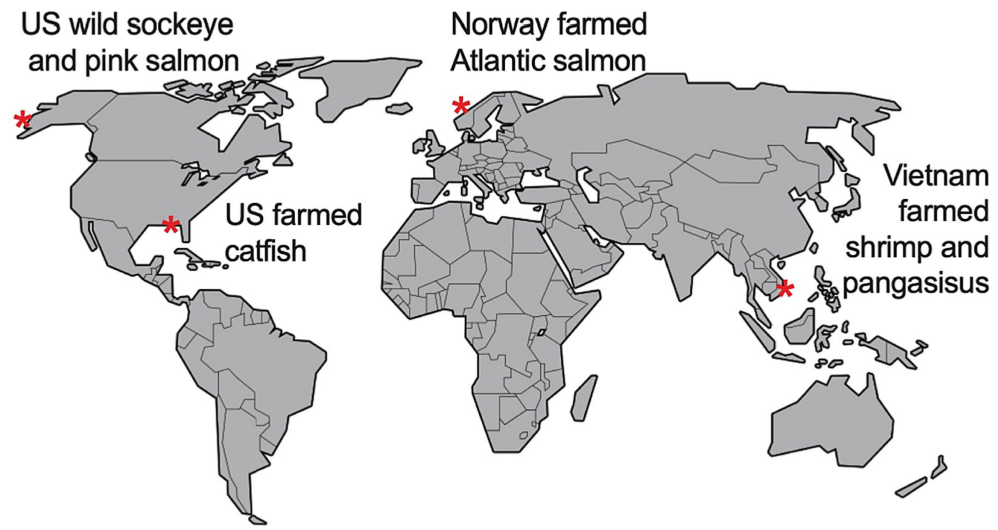

FIGURE 1
Study sites.

1.1.2 United States Alaska wild capture pink salmon

The Alaska wild capture pink salmon fishery operates in nearshore waters of Prince William Sound. Pink salmon are caught using purse seines from July to August (description of purse seines).[2] The fishery harvests about 60 thousand tonnes of pink salmon annually, valued at $55 million USD (Alaska Department of Fish and Game (ADFG), 2022), and more than 60% of the catch is hatchery-origin fish (Wilson, 2022). Pink salmon are less valuable than sockeye salmon due to their lower oil content, and a high share of the pink salmon harvest is canned.

1.1.3 Norway farmed Atlantic salmon

Norway, the largest producer of farmed Atlantic salmon, produces 1.4 million tonnes of farmed salmon, which represents 51% of global farmed Atlantic salmon production (FAO, 2022). Salmon farming involves two stages: land-based freshwater rearing of eggs to smolts (i.e., the lifestage when salmon transition to saltwater), and grow-out of smolts to adults in coastal or offshore net pens. During the 1–2 year grow out cycle, salmon are fed pelleted feeds. The limited ability to control the environmental conditions in the net pens has resulted in high mortality attributable to diseases and parasitic infestation, primarily salmon lice (Overton et al., 2019). To decrease exposure to risks during pen-rearing, producers are rearing smolts to larger sizes in land-based systems and reducing the time spent in ocean net pens (Ytrestøyl et al., 2020), however, this increases energy and water use.

1.1.4 United States farmed catfish

The US farmed catfish industry is the largest aquaculture sector in the US, with an average production of 150 thousand tonnes annually. Catfish farming occurs primarily in Alabama and Mississippi. Catfish aquaculture has two production phases: a hatchery phase that occurs in indoor tanks and a grow-out phase that occurs in 4–5 ha freshwater ponds. During the 18-month grow-out period, the ponds require mechanical aeration to increase dissolved oxygen levels; rotating paddle wheel aerators are the most commonly used (description available here).[3] Catfish are harvested at 1.7 pounds and primarily shipped as frozen filets and consumed in the US. Catfish are the seventh most consumed seafood in the US.

1.1.5 Vietnam farmed pangasius

Vietnam is the largest producer and exporter of pangasius with China, the US, and Europe as the main markets (Nguyen et al., 2023). Nearly 1.5 million tonnes of pangasius are farmed annually in Vietnam (Vietnam Association of Seafood Exporters and Producers (VASEP), 2019). Pangasius farming occurs in earthen ponds near river tributaries. The ponds are filled with water pumped from the adjacent water bodies. There are three stages of pangasius culture: hatchery ponds for rearing larvae to fry, nursery ponds for rearing fry to fingerlings, and grow-out ponds. Pangasius are capable of breathing air. Therefore, farming of pangasius does not require aeration, unlike similar farmed species such as catfish.

1.1.6 Vietnam farmed shrimp

Vietnam is one of the leading producers of farmed shrimp with production of 879 thousand tonnes annually (Vietnam Association of Seafood Exporters and Producers (VASEP), 2020). Production is comprised of whiteleg shrimp (*Litopenaeus vannamei*) and giant tiger prawn (*Penaeus monodon*), and occurs primarily in the Mekong Delta region. Shrimp broodstock are spawned and larvae are reared in indoor, recirculating tanks. Post-larvae shrimp are stocked into brackish ponds (i.e., water with salinity levels in between freshwater

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[2] https://www.fisheries.noaa.gov/national/bycatch/fishing-gear-purse-seines

[3] https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=34100.wba

and seawater) filled with water pumped from nearby canals and rivers mixed with seawater, and aerators are used to support higher stocking densities. Shrimp is the most consumed seafood in the US and a high share is purchased at retailers, such as grocery stores (Love et al., 2020).

1.2 Research questions

The purpose of the study was to answer the following research questions:

1 What are the main uses of water and energy in each stage of the supply chain, and how has resource use changed?
2 How are usage, costs, and availability of water and energy perceived by seafood supply chain actors?
3 What strategies are used by seafood supply chain actors, or are identified as potential strategies, to reduce energy and/or water use? What are the key motivating factors and barriers to implementation?
4 Where in seafood supply chains are there synergies and tradeoffs between water and energy use? How do synergies and tradeoffs vary by stage of the supply chain and across selected supply chains?

2 Methods

The FEW nexus was the overarching framework used for this study, and we applied it to the six seafood supply chains using a multiple-case study design. A multiple-case study design allows researchers to study cases that exist in different contexts and compare and contrast them (Yin, 2009). The FEW nexus informed the research questions and methods for data collection and analysis. At the same time, we used an inductive, descriptive approach to data analysis instead of developing and testing hypotheses within the FEW nexus (additional details on data analysis are below).

This work was part of a larger study that involved primary and secondary quantitative data collection, consumer surveys, and separate case studies. The larger effort spanned additional supply chain stages and included waste of seafood. This study provides qualitative results from stakeholders that compliment quantitative aspects of the overall study. The quantitative data we collected on the six seafood supply chains are not reported in this paper, but just as the qualitative data contextualized the quantitative data, the quantitative data was used to check and improve our understanding of the qualitative data. Mixed-method and quantitative results from the larger study have been published (Brown et al., 2022; Scroggins et al., 2022; Viglia et al., 2022a,b; Love et al., 2023a) and other results are forthcoming.

In this paper, water use includes all freshwater that serves a purpose at an operation. We include some information about sea water to fully describe certain supply chain stages, but we did not explore strategies to reduce use of sea water. Other parts of our overall research effort used a lifecycle inventory approach to quantify water use and defined water use consistent with the concept of "blue water" (Chapagain and Hoekstra, 2008), as water that has been sourced from surface or groundwater resources and has either evaporated, been incorporated into a product, or taken from one body of water and returned to another (e.g., surface water pumped onto a farm and discharged into the same body of water would not be considered "water use"; Viglia et al., 2022a). Using a broader definition in this study was consistent with how interviewees interacted with water and enabled exploration of important issues identified by interviewees that did not fit the narrower definition.

From 2019 to 2021, we conducted 47 semi-structured interviews. Interviewees were recruited through industry and academic contacts, and using chain sampling (i.e., snowball sampling). Chain sampling involves one interviewee referring the research team to one or more contacts who may be willing to be interviewed. Recruitment methods for the overall study, including the qualitative interviews, are described in more detail elsewhere (Brown et al., 2022; Scroggins et al., 2022; Viglia et al., 2022a,b). The majority of the interviewees (44) were employees or owners of feedmills, hatcheries, commercial fishing boats, fish farms, and processing plants (Table 1). These interviewees were mostly business owners or middle/upper management, so they generally provided business-level perspectives. In addition, we were referred to and interviewed three experts based on their role in a relevant government agency or as a representative of a trade group supporting one of the supply chains in the study. These interviewees provided complementary sector-level perspectives for wild-caught sockeye salmon and farmed pangasius (Table 1). Several interviewees represented more than one stage of the supply chain; for example, interviewees whose business included multiple stages provided information about hatchery and grow-out operations, or grow-out and processing. The study was approved by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board (IRB no. 8345). Key aspects of data collection, data analysis, and the structure of the results section are summarized in Figure 2.

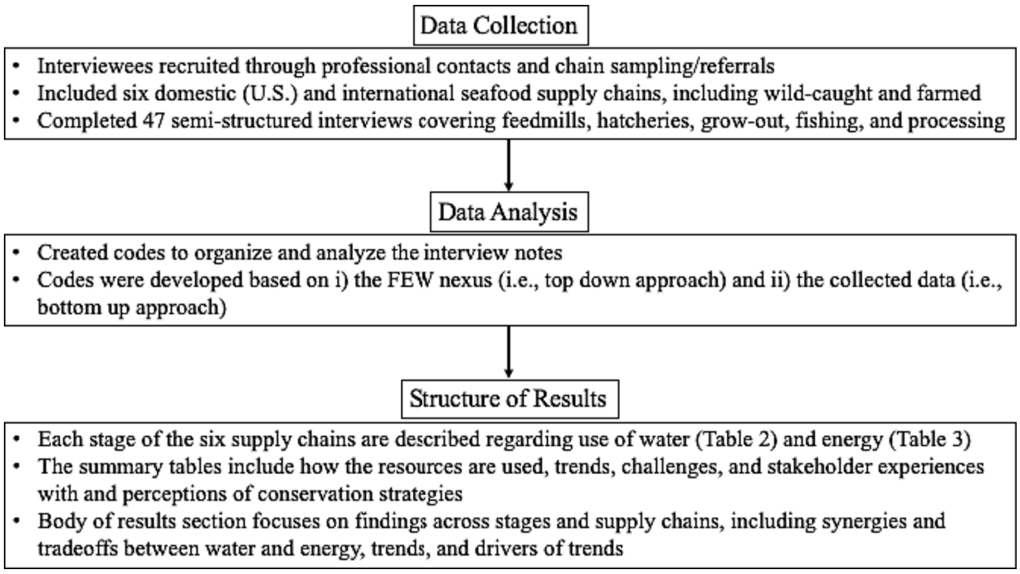
The interviews were semi-structured; interviewers used a list of questions and potential probes, and also asked follow-up questions that were not pre-written. The first set of questions focused on water use (Appendix), including how water is used by the business, how water use has changed and drivers of any changes (if applicable), current and potential strategies to reduce water use, and motivations and barriers related to adopting water conservation practices. The second set of questions focused on energy use and covered the same topics. Interviewers also asked questions about the amount of seafood that is wasted at each supply chain stage, and those results are reported elsewhere (Love et al., 2023a). The final questions were about general challenges facing the business or sector and how the business prepares for future challenges. Questions about the impacts of the COVID-19 pandemic were added to the questionnaire in 2020.

Interviews were conducted in person, over the phone, or via Zoom (Zoom Video Communication, Inc., San Jose, CA, United States). Notetakers participated in all interviews to accurately capture responses. The audio of phone and Zoom interviews was recorded to allow the research team to check their notes, except for two interviewees who were not comfortable being recorded.

We analyzed the data using a combination of deductive and inductive approaches. A deductive approach to qualitative data analysis involves applying pre-determined codes to the data, and this approach is often used to test whether data is consistent with an existing theory (Creswell, 2007). An inductive approach does not have pre-determined codes, and instead involves developing codes based on the collected data and then applying those codes across the data. Combining deductive and inductive data analysis techniques is

TABLE 1 Study sample.

Seafood type	Country	Number of interviews	Modality	Year(s) interviews were conducted	Supply chain stages and/or experts represented
Farmed catfish	US	5	In-person and phone	2019	Feedmills, hatcheries, grow-out ponds, processors
Wild-caught sockeye salmon	US	8	Phone and Zoom	2020–2021	Drift net fishers, processors, government regulator, trade group representative
Wild-caught pink salmon	US	4	Phone and Zoom	2020–2021	Fishers, processors
Farmed pangasius	Vietnam	11	In-person	2019	Feedmills, hatcheries, grow-out ponds, processors, government representative
Farmed shrimp	Vietnam	9	In-person	2021	Hatcheries, grow-out ponds, processors
Farmed Atlantic salmon	Norway	10	In-person	2019	Feedmills, indoor freshwater tanks, grow-out sea-based net-pens, processors



Data Collection

- Interviewees recruited through professional contacts and chain sampling/referrals
- Included six domestic (U.S.) and international seafood supply chains, including wild-caught and farmed
- Completed 47 semi-structured interviews covering feedmills, hatcheries, grow-out, fishing, and processing

Data Analysis

- Created codes to organize and analyze the interview notes
- Codes were developed based on i) the FEW nexus (i.e., top down approach) and ii) the collected data (i.e., bottom up approach)

Structure of Results

- Each stage of the six supply chains are described regarding use of water (Table 2) and energy (Table 3)
- The summary tables include how the resources are used, trends, challenges, and stakeholder experiences with and perceptions of conservation strategies
- Body of results section focuses on findings across stages and supply chains, including synergies and tradeoffs between water and energy, trends, and drivers of trends

FIGURE 2
Summary of methods and structure of results.

beneficial because it allows researchers to analyze the data using codes created based on an existing theory (i.e., "top down") and codes that emerge from the collected data (i.e., "bottom up"), resulting in a robust understanding of the cases that is not limited to one approach. We developed codes prior to data analysis that aligned with the subtopics and concepts in the research questions (section 1.2). This part of the analysis process applied the FEW nexus framework to the data and was deductive (Creswell, 2007). Codes included: current energy use, changes in energy use, current energy conservation strategies, potential energy conservation strategies, motivating factors, etc. Similar codes were developed for water, as well as codes for interactions between water and energy that involve synergies and/or tradeoffs. We also used inductive analysis techniques (Creswell, 2007); we developed additional codes based on the collected data and focused on creating rich descriptions for each seafood supply chain, or "case." Codes were applied to the detailed notes from each interview to organize and analyze the text. Data analysis involved examining text relevant to synergies and tradeoffs, and identifying similarities and differences across stages and supply chains. Coding and data analysis were completed using MAXQDA (VERBI Software, Berlin, Germany) and Excel (Microsoft Corp., Redmond, WA, United States).

Results from qualitative interviews are used to better understand how issues impact people and groups, including businesses, and how related issues interact. Qualitative research methods are not designed to generate results that are quantifiable, and due to our sampling methods, our results cannot be interpreted as representative of a larger population (i.e., supply chain actors who were not interviewed). Therefore, the results are reported using descriptive language and do not include the number of interviewees who gave a certain response.

3 Results

As summarized in Figure 2, study results are presented in tables and a narrative. Descriptive summaries for each supply chain, by stage, are presented in Tables 2, 3. Information in the tables include the source of water or type of energy, the main uses of each resource, stakeholders' perceptions, trends, challenges, and current and potential conservation strategies. The text below focuses on findings across the stages and supply chains, including synergies, tradeoffs, trends, and factors driving trends.

3.1 Water

Freshwater is used in aquaculture supply chains during the production of feed and to fill tanks and ponds at the hatchery and grow-out stages. Water is used similarly during processing in wild and farmed seafood supply chains; the most common uses are cleaning fish, washing equipment and the plant, and making ice (Table 2). The fishing stage of the wild-caught salmon supply chains are not included in Table 2 because the fishers we interviewed used small amounts of freshwater for cooking, bathing, and other personal uses. Some fishers in these supply chains use ice to chill their fish, and the ice is supplied by the processors. Therefore, this use of water is included with the salmon processors.

Across supply chains, interviewees explained that direct costs of water did not motivate businesses to identify or implement water-saving strategies (Table 2). This response was consistent regardless of water source, including groundwater via wells, surface water via pumps, water from a local utility, or a combination. Many stressed this point by comparing their water costs to their energy costs, and the latter were often many orders of magnitude higher. Nonetheless, some interviewees identified relevant conservation strategies. The most common water-saving strategies that interviewees used, or were interested in using, were: purchasing equipment that is more efficient, reuse and recirculation of water, reducing use of ice in shipping, and training employees to avoid wasting water (i.e., turn hoses off when not in use).

In addition to viewing water as cheap, especially regarding direct costs, water was widely described as plentiful. This was true even when evidence of declining water availability in the local area or region came up later in the interview or with another interviewee in the same geographic area. For example, catfish farms in the US rely on groundwater and/or precipitation to fill ponds. Some interviewees that use groundwater stated at the beginning of the interviews that they were unconcerned about water cost and availability, but dropping water levels in local aquifers and the need to dig deeper, more expensive wells came up later in some of the interviews. Researchers have described this phenomenon and argued that it shows the value of conducting qualitative interviews for exploring inconsistent answers in response to different issue framing (Bercht, 2021).

Although direct costs of water were not a major concern, it was common for interviewees to describe other costs that are tied to water use and/or water quality when asked about water use and water-saving strategies. Common costs related to water included energy (e.g., pumping, cooling, and heating), water treatment supplies, and wastewater treatment and/or disposal. In Vietnam, producers generally only have access to surface water, and declining water quality attributable to broader industrialization and urbanization is a widespread concern (Thanh Giao et al., 2021). Fish and shrimp farmers have invested in equipment and water treatment supplies, and used space on their farms as settling and/or treatment ponds. A settling pond holds water that is pumped onto a farm and allows suspended solids to collect on the bottom, resulting in improved water quality. They also recirculated the water to minimize the volume of surface water coming onto the farm that needs to be treated. The motivation to increase recirculation in Norway is different, but it is also related to water quality. Fish farmers in Norway have increased the time fish spend in the land-based, freshwater production stage before transitioning to coastal or offshore net pens to minimize disease risk (Ytrestøyl et al., 2020). The net pen growout stage involves little direct use of freshwater. In addition, the production of smolts in freshwater has shifted from flow-through to recirculating operations.

3.2 Energy

Sources of energy used across supply chains were electricity from a local power utility, diesel, gasoline, solar panels, and backup generators (Table 3). Energy was used for refrigeration, and to power a variety of types of equipment, fishing vessels, and vehicles.

Among most interviewees, there was strong interest in energy conservation strategies, and reducing costs was the main motivation (Table 3). Salmon fishermen were an exception; they explained that other costs were higher on an annual basis (e.g., labor, insurance, nets) and that they viewed the amount of fuel used each season as something that would be very difficult to change. A key reason is the importance of speed while fishing; the sockeye salmon fishery is one of the most compressed fishing seasons in the world, lasting about 2 weeks, and vessels compete with one another in a 'race to fish' (Hilborn, 2007). Boats need to (i) quickly reach specific areas that are temporarily opened for fishing by regulators, (ii) compete with one another to catch available fish, and (iii) avoid dangerous weather.

Common energy-saving (or cost-saving) strategies used by interviewees were LED lights and motion detectors, soft start motors, regular maintenance of equipment, purchasing new energy-efficient equipment, using electricity during off-peak times, training staff to avoid unnecessary energy use, reusing hot water for another purpose, and minimizing equipment stops and starts (feedmills and processors).

Across supply chains and stages, many operations have become more energy intensive over the past several years, according to interviewees. In aquaculture production, this was described as being driven by increased aeration and use of filters and pumps needed for recirculation and/or to accommodate higher stocking densities. US catfish farms use electricity to run aerators at night for fish health/survival and to accommodate higher stocking densities. Pangasius producers in Vietnam do not have the same need for aeration because pangasius can breathe air, but, as described above, some pangasius and shrimp farmers in Vietnam are using equipment to recirculate water and increase oxygen levels in ponds in response to declining water quality. Compared to salmon production methods in use in recent years, farms are now growing fish to a larger size in the freshwater stage to shorten the amount of time spent in open net-pens where salmon are vulnerable to disease pressures, like sea lice, and this increases energy use.

Energy use has shifted and potentially increased in the two Alaskan fisheries in the study. In recent years there has been a major shift toward chilling fish on boats using ice slurries or refrigerated sea water (RSW) systems. These systems chill sea water in holds and are either powered by the main engine of the boat or a separate, smaller engine. For boats that do not have RSW systems, ice is provided by

TABLE 2 Descriptive summaries for water.

	Source(s)	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Farmed catfish (US)				
Feedmill	Local water utility	An ingredient in fish feed and steam*	Lower priority due to low cost of water compared to energy	Replace equipment with newer, more efficient equipment that save water and energy* Cost-share programs to support purchases of new equipment Interested in reducing the moisture level of feed during production to reduce energy needed for drying*
Hatchery	Groundwater and precipitation	Water used for rearing eggs and fry indoors and in ponds	Water quality (and proper temperature) is critical for this life stage	One hatchery described a new process that was developed that increased survival and decreased water used per unit of production*
Grow-out	Groundwater and precipitation	Fill ponds and replace water in ponds lost due to evaporation, seepage, draining for harvesting, or when rebuilding ponds	Lower priority because not charged for groundwater Interested in using less water to reduce energy costs for running wells and pumps* Water table is getting lower and digging deeper wells is more expensive	Deeper ponds can be dug to allow space for rain capture and to reduce evaporation compared to volume of water in ponds* Cost-share programs to support digging deeper ponds
Processing	Local water utility	Clean fish, wash equipment and plant, and make ice*	Lower priority due to low cost of water compared to energy Regulatory requirements for washing equipment have increased under USDA oversight of catfish processing plants, generally seen by plant managers as unnecessary and not beneficial for food safety Increased automation, in part due to labor challenges	Conduct staff training to avoid wasted water Increased automation, including using water jets to cut fish
Farmed pangasius (Vietnam)				
Hatchery and Grow-out	Surface water	Fill ponds and replace water in ponds that is lost due to evaporation, seepage, and release of effluent	Decreasing water quality is an issue, especially for sites located near or downstream from rice farms: producers use settling ponds and other treatment strategies, which are contributing to rising production costs	Producers avoid pumping water into the farm when nearby rice farms release effluent due to pesticide contamination Desire for regional planning and coordination, for example so rice farms are not near fish farms Interested in systems that will filter and recirculate the water, but the equipment is expensive
Processing	Groundwater	Clean fish, wash equipment and plant, and make ice*	Reducing the volume of water used is not a priority due to the low cost of water compared to energy costs, but reducing water use can reduce costs of treatment before wastewater is discharged Processors are concerned about pressure from the government to shift to using surface water; processors want to keep using groundwater due to concerns about poor water quality and the cost of water treatment	A site that has a feedmill and processing plant uses hot water from the feedmill for cleaning in the processing plant*

(Continued)

TABLE 2 (Continued)

	Source(s)	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Wild-caught pink and sockeye salmon (US)				
Processing	Surface and groundwater Local water utility	Store and clean fish, wash equipment and plant, make ice*, and cook and cool cans*	There are no concerns about availability of freshwater and little to no motivation to conserve water (unless there is an associated cost savings related to energy use) because the water table is high and there are many streams and rivers Note: interviewees also described localized/isolated water availability issues related to hot, dry summers; some instances were many years ago and some were recent Canning: processors do not re-use water used for cooking and cooling; infrastructure required for water reuse would be expensive and water is seen as plentiful	Could cool down hot tank and reuse water instead of dumping the water
Farmed Atlantic salmon (Norway)				
Feedmill	Local water utility	An ingredient in fish feed and steam*	Using less fishmeal in feed has resulted in using more water to get the feed ingredients to bind properly Availability and direct costs of water are not a concern, but reducing use of water in the production of feed would result in reduced energy costs*	Interested in improved processes for extrusion and drying feed that would use less water and energy*
Freshwater	Surface water	Fill tanks and replace water lost due to release of water and evaporation	Water seen as cheap and plentiful Fish are now kept in this stage of production longer (and in sea cages for a shorter amount of time) to reduce disease risk and improve growth, this increases overall energy use in production of farmed At. salmon* Sites used to be flow-through and have moved to recirculating some or all of their water, this requires more energy for pumps and other equipment*	Increased use of water filters and treatment to allow for recirculation* Interested in technology that reduces evaporation
Processing	Local water utility and surface water from fjords	Store and clean fish, wash equipment and plant, and make ice*	Water is seen as cheap and plentiful, but one processor said they may start making their own freshwater due to increasing prices Have had to use more ice over time due to changing standards of a certification organization*	Interested in reducing the volume of ice used in shipping due to the weight of the ice and the space it occupies, one processor is using technology to chill fish before freezing and others are interested*

(Continued)

TABLE 2 (Continued)

	Source(s)	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Farmed shrimp (Vietnam)				
Hatchery and grow-out	Hatcheries: filtered sea water and groundwater (<5%) Grow-out: surface water from sea and rivers	Fill ponds and replace water in ponds that is lost due to evaporation, seepage, and release of effluent	Declining quality of river water is a concern	Some hatcheries are using filters and UV treatment to allow for recirculating water, allows them to save money on energy used for pumping* (because they are pumping around the farm instead of pumping water into the farm) and wastewater treatment/disposal Desire better treatment strategies for surface water Many producers now dedicate 60–70% of farm area to water treatment and/or settling, this allows for higher stocking density in the production area because the water is cleaner, they are using more electricity*, strategies used: water filters (e.g., activated carbon), disinfection (e.g., UV), oxygen blowers Note: Not all producers have room on their farm to dedicate to water treatment so they cannot adopt this production model
Processing	Groundwater	Clean equipment and plant, and make ice*	View high use of water as costly due to the associated costs of pumping water* and treating wastewater	Have reduced the volume of ice used when storing shrimp* and installed low flow faucets Train employees to reduce water (and energy) use, one processor tracks and includes these efforts in rewards/promotions for plant staff

*Aspect of operation that involves synergy or a tradeoff between water and energy use.

processors. Chilling sea water or making ice requires energy. A benefit of onboard chilling and improved storage is higher quality fish that can be sold fresh or frozen instead of canned. The share of Alaskan salmon that is canned has declined significantly in recent decades. Canning uses a great deal of energy and water in processing, however, as more salmon from Alaska are sold fresh or frozen, energy is used to (i) chill fish on boats, (ii) keep fish chilled or frozen at processing plants, during transport, and at other stages of the supply chain, and (iii) transport some fish in airplanes. These are significant shifts compared to using energy and water to cook and can fish and then ship and store shelf-stable seafood products. It is not clear from our interviews whether overall energy use in these supply chains has increased.

Some processing plant interviewees described trends toward using more per-unit energy than previously due to increased refrigeration capacity, ice production, water chilling, automation, and/or use of hot water for cleaning. There was wide variation regarding the extent of automation in processing plants across seafood supply chains. In Vietnam, workers processed seafood by hand, and in Norway processing was highly automated. The US-based processing plants in our study used some automation and were generally interested in increasing automation. Using more automation requires additional energy, and some machines also use water. For example, some machines use jets of water to cut fish. Interviewees explained that an important reason that US plants were interested in automation was difficulty attracting and retaining workers, especially in rural and/or geographically isolated locations.

3.3 Water-energy synergies and tradeoffs

Use of water and energy were directly coupled in several ways in the production and processing stages of seafood supply chains. Various sources of energy were used to pump, heat, and cool water. Large volumes of water were involved in many of the operations, and energy, usually in the form of electricity, was used to move water with pumps. Energy was also used to create hot water, steam, cold water, and ice. Depending on the processing plant, hot water was used for cleaning and during canning. Feedmills used steam to cook fish feed. Water was cooled on fishing vessels that have RSW systems and in processing plants to chill fish (storing fish in water also prevented crushing). Processing plants made ice to keep products in boxes or other types of containers cool when they were shipped, and processing plants in Alaska also made ice and provided it to fishers who lacked

TABLE 3 Descriptive summaries for energy.

	Source(s) and types	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Farmed catfish (US)				
Feedmill	Local electrical power utility and diesel	Power machines and a boiler, also used to heat water+, and heat and dry the feed+	Reducing energy use for cost savings is a priority, shared estimate that energy costs can be 10 to 25 times higher than water costs Finding grant opportunities and applying for them is a challenge due to the staff time needed to network, conduct research, and complete the application Equipment is highly specialized and different from machines used to make feed for livestock and pets, so there has not been much innovation	One interviewee applied for and received a grant that partially paid for new equipment, including a new boiler, that uses less energy (and water)+ Interested in streamlined information on potential grants, cost-share programs, etc. Considering increasing storage capacity for finished feed to reduce stopping and starting the equipment (starting the feedmill equipment is energy intensive) Interested in more carefully controlling the moisture level in the feed during the production process to reduce the energy used to heat the water and dry the feed+
Hatchery and Grow-out	Local electrical power utility, diesel, gas	Run aeration devices and pumps+, vehicles, and other equipment	Ponds aerated at night to allow higher stocking density, in the past they ran diesel tractors at night and now use electricity to run auto O2 sensors and aerators (tractors are kept for backup) Electricity from the local utility in the region is cheap compared to other regions of US, low rates are important for the growout stage Power used for aeration is needed at night so it is off-peak, high use is seasonal, monthly power bill can be up to \$10 k Gas is used to run trucks around some farms for many hours to fend off birds that take catfish from ponds to eat Volatility and competition in the catfish sector prevents commitments/investments that could improve efficiency because producers are hesitant to take on additional costs/debt	USDA Rural Energy for America Program (REAP) programs help with energy use (have helped pay for auto O2 monitoring in ponds) but applications require a lot of paperwork and time Run wells and pumps at night to pay off-peak electricity rates Interested in a more efficient aeration device to save money, running 3,000 hp. each night, but it would also need to be sturdy/long-lasting due to heavy use Hatchery: One described a new process that was developed that increases survival and decreases energy used per unit of production+
Processing	Local electrical power utility and diesel	Power machines, refrigeration, and make ice+	Using more energy due to added refrigeration used to make ice, freeze product, run air conditioning, and chill water It is difficult to implement energy saving strategies that disrupt production because plant runs year-round Electricity from the local utility in the region is cheap compared to other regions of US, low rates are important for the processing stage Oversight from USDA and third-party seafood certification organizations have led to increased energy use	Use LED lights, more efficient motors (e.g., soft start, variable drive), better refrigerator doors, motion lights, monitor heat loss, increase use of off-peak power, regular maintenance of machines The above strategies are implemented gradually as areas of the processing plant are remodeled or newly built, or as machines wear out

(Continued)

TABLE 3 (Continued)

	Source(s) and types	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Farmed pangasius (Vietnam)				
Hatchery and Grow-out	Local electrical power utility	Run pumps+	Electricity costs are going up, but discounted business rates are available in some places Availability of peak/off-peak rates varies by geographic area There is frustration with a lack of help or support from Pangasius companies and/or government agencies	Use smaller pumps when possible Use efficient lights and pumps, work and run pumps at night to avoid peak electricity rates Interested in solar, but producers are worried about costs and the rainy season
Feedmill and Processing	Local electrical power utility, solar, diesel	Power machines and generators, refrigeration, make ice, and heat and dry feed	Strong interest in continuing to improve energy efficiency due to cost savings	Use efficient lights, soft start motors, and staff training, utilize off-peak electricity, and purchase processing equipment that is more expensive and efficient Use efficient method to freeze filets faster Interested in solar power Interested in pulling waste heat from feedmill to heat water for processing plant
Wild-caught pink and sockeye salmon (US)				
Fishing	Diesel	Power fishing vessels and cool seawater and fish in refrigerated sea water systems	Reducing fuel costs is not a top priority because speed is important to reach open fishing areas quickly and to avoid bad weather, also there are other costs that are higher in a typical season (e.g., nets, labor, insurance) Fishery has shifted from dry fishing to use of ice or RSW to keep fish chilled, processors pay a premium for chilled fish (e.g., $0.15 extra per pound) Owner-operated vessels in these fisheries can make innovation challenging because: (i) owners have many competing roles and (ii) investing in a new strategy or technology involves risk and it is hard to predict the return on investment Investments that reduce energy use take longer to pay off due to the seasonal nature of these fisheries, alternatively there is time for installation due to the seasonal nature of the fisheries The management of the fishery is focused on allocation, often a small space is open for fishing and the opened space the following day might be 100 miles away, fishers must get there quickly Sockeye: length limit for fishing boats is 32 feet and boats have become wider to hold more fish, this is not an efficient boat design	Fishers use (or sometimes use) LED lights, fuel flow meters, engine maintenance, energy audits The RSW can be run separate from the main engine so the main engine can be turned off when the boat is idling in line to deliver fish (this can take hours) or idling for other reasons Interested in incorporating batteries that would allow them to reduce or eliminate use of diesel when idling, one interviewee installed an inverter and a battery that charges phones and other devices to improve crew morale Having multiple, smaller holds for fish instead of one large hold can increase cooling efficiency, but the work required to create multiple holds would be expensive There are state and federal loan programs focused on efficiency improvements that are helpful, but the costs of the equipment or upgrades have gone up and the loan limits have not increased Delivering fish to a tender vessel, instead of a processing plant, saves fuel Sockeye: fishers stated that increasing the boat length limit from 32 feet to 34–36 feet would improve fuel efficiency, but they also note that increasing the length limit is politically unfeasible

(Continued)

TABLE 3 (Continued)

	Source(s) and types	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Processing	Local electrical power utility and diesel	Power machines, boiler, and generators; refrigeration, make ice+, create steam to cook cans, and power tender vessels for transporting fish to plants	Tender vessels: Reducing fuel costs is not a top priority because speed is important to coordinate timing with tides and to avoid bad weather; processors will send additional tenders out beyond needed space capacity to unload fish so fishers can return to fishing faster Fishing boats without RSW systems are supplied with ice from processors+ Labor challenges, in part due to isolated geographic locations, drives interest in automation but it is hard to justify the cost when it would only be used 2–4 months out of the year (alternatively, downtime to install equipment or perform maintenance is not an issue) Processing plants are charged extra when energy demand spikes and keeping demand at a steady level during a short, intense fishing season is not always possible Processing plants sometimes experience power surges that have blown transformers and damaged other equipment	Plants use LED lights and efficient soft-start motors to reduce startup load Interested in larger processing equipment to handle more fish with fewer machines Plants manage electricity demand to the extent possible, for example by making ice at strategic times when the plant is using less electricity to avoid demand spikes Interested in purchasing large batteries to create constant power and to avoid surges Interested in more hydropower in Alaska to improve electricity infrastructure
Farmed Atlantic salmon (Norway)				
Feedmill	Local electrical power utility and diesel (<1%)	Heat and dry feed	Energy is expensive, especially compared to water Moisture level and drying is important during the production process	A group of staff is on an energy team to identify ways to reduce energy use/costs Have reduced the need for rework by paying close attention to moisture levels and other issues Minimize stopping and starting equipment because starting is energy intensive Regular maintenance of feedmill equipment
Freshwater rearing	Local electrical power utility and diesel, backup generators	Run pumps+, cool or heat water, automated feeding, and power generators and vehicles	Energy seen as cheap and abundant in Norway Moved on land to deal with lice and other env issues, uses more energy Use seawater taken from 80 m deep to heat/cool freshwater, use heat pump Hesitant to buy solar panels because they get better every year Positive views of government regulations	Monitor energy use and costs every month, LED lights Planning some solar panels Work with academic researchers

(Continued)

TABLE 3 (Continued)

	Source(s) and types	Major use(s)	Perceptions, trends, and challenges	Current and potential strategies
Grow-out	Local electrical power utility and diesel, backup generators	Power vessels and equipment on net-pen platforms	Platforms and net-pens have moved farther away offshore The mix of electric and diesel depends on how far platforms are from land, it is expensive to run electric cables far offshore	Have electrified some platforms and boats to reduce use of diesel Electrifying may involve batteries and renewable energy sources, especially for platforms far offshore Interested in wet feeding (vs. air feeding) to save energy, but concerned about feeding equipment getting clogged
Processing	Local electrical power utility	Power machines, refrigeration, freezing	Requirements for product cooling and plant cleaning (with hot water+) have increased, certifications add a layer of difficulty Energy is seen as cheap and abundant by interviewees	Use LED lights, motion sensors, and equipment upgrades Cool fish before packing to use less ice+ (still uses energy but less water used as ice) When cooling hot water, it is used to pre-heat cleaning water [this could be done in other plants and is not common according to other interviewees]
Farmed shrimp (Vietnam)				
Hatchery and Grow-out	Local electrical power utility and backup generators	Run pumps and recirculating equipment+	Electricity prices have been increasing More electricity is being used for pumps, oxygen generators, filters, and other equipment due to water quality issues that are linked to shrimp health and survival Hatcheries: using more electricity to run pumps and other equipment for a recirculating system Growout: using more electricity to support higher stocking density and a two-stage production model via pumps, oxygen generators, filters for recirculating	Interested in solar, heard from one producer with solar who uses a lot of power to deal with poor water quality and allow intensive production (i.e., higher stocking density)
Processing	Local electrical power utility, diesel, and backup generator	Refrigeration, diesel to power vehicles and for steaming	Energy costs are increasing Saving energy is not a priority because they are focused on purchasing inputs and hiring more staff Many energy-saving strategies are expensive to implement and it is difficult to change people's behavior (i.e., staff)	Interested in solar panels Plant trains employees to reduce energy use (and water), one processor tracks and includes these efforts in rewards/promotions for plant staff Desire consistent government policies that support adoption of renewables

+Aspect of operation that involves synergy or a tradeoff between energy and water use.

RSW systems to cool fish on the vessel. Due to water and energy being linked in these ways, improving efficiency of water use can result in improved efficiency for energy.

As described above, water quality issues have resulted in increased energy use in some aquaculture production settings. A key tradeoff is that increased reuse or recirculation of water during hatchery and production stages of aquaculture reduced the volume of water used and increased use of energy to run filters, pumps, and other equipment. Also, extending the length of the freshwater stage and adoption of recirculating technology in Norway has increased the overall amount of energy used to produce farmed salmon. These changes have important benefits, like improved survival rates.

There are also instances where it is unknown how changes in the use of one resource impact use of another. Some processing plant personnel were using, or were interested in, equipment that chills products in a manner that reduces the need for ice during shipping. The main benefit of using the equipment was to reduce per-unit shipping costs by reducing the weight and space that ice takes up in shipping. The strategy would reduce water use, but it is not clear based on our interviews how energy use is impacted by adding the chilling equipment and making less ice.

3.4 Challenges related to the few nexus

3.4.1 Disease pressures

Across all aquaculture supply chains, diseases during hatchery and/or grow-out stages were a major concern. A disease outbreak can sicken or kill a large number of fish or shrimp and result in a major economic loss (Quezada and Dresdner, 2017; Asche et al., 2021). Losses due to disease reduce overall efficiency of operations regarding use of water and energy per-unit of production.

3.4.2 Impacts of the COVID-19 pandemic

Due to the timing of interviews, stakeholders working in the farmed shrimp and two wild salmon supply chains were asked about impacts of the COVID-19 pandemic on their businesses and sector. Impacts on demand for seafood during the pandemic have been described in detail in other studies (Love et al., 2021; van Senten et al., 2021; Anderson et al., 2022; Sun et al., 2022; Engle et al., 2023; Love et al., 2023b). Interviewees in this study described effects on demand for products that varied across supply chains and over time. Demand remained strong for farmed shrimp, although some price volatility occurred. There was a decrease in demand for sockeye salmon caused by widespread closure of restaurants, but demand subsequently rebounded due to interest in cooking sockeye salmon at home. Demand for canned pink salmon increased early in the pandemic, and processing plants had a hard time meeting demand due to constraints on labor and access to raw materials. Domestic landings were moderately down during the pandemic, while imports increased.

There were significant labor challenges in all three supply chains, and processing plants seemed to be most impacted. Due to the short fishing seasons and isolated geographic location, salmon processing plants in Alaska rely on workers who fly in from other parts of the US and other countries, so travel disruptions added an additional layer of difficulty for these businesses compared to processing plants in other settings that rely on local workers. Processing plants also had increased costs associated with social distancing and purchasing additional protective equipment for workers.

The supply chains also experienced increased costs of inputs. In response to increased prices for commercial shrimp feed, one producer supplemented with local, noncommercial feed sources. The farmed shrimp sector also experienced higher shipping costs and general disruptions attributed to the pandemic. This is a key part of the supply chain since exports are important for the farmed shrimp sector in Vietnam.

3.4.3 Requirements from government agencies or certification organizations

Processing plant operators described new requirements related to regulations or certification programs. They described requirements for cleaning the processing plant and using more ice during shipping as main drivers for increased use of water and/or energy. The requirements were viewed by plant operators as unnecessary for ensuring food safety or preventing other issues.

3.4.4 Climate change

When asked about future threats to their businesses, climate change was brought up by several interviewees. In addition, the warming climate was linked to increased energy use by interviewees in two supply chains. One Alaskan pink salmon fisherman explained that there had been a couple of unusually warm summers and some RSW systems did not have enough capacity to properly cool the sea water and fish. They said that some fishermen in Alaska were investing in larger RSW systems to avoid that issue in the future. A manager at a catfish processing plant said that higher ambient temperatures have made it difficult to keep the plant and fish cool and requires additional air conditioning, especially when outside air enters the plant during deliveries.

3.5 Stakeholder experiences with resource efficiency strategies

Many interviewees explained that they were hesitant to invest money and/or time into a resource conservation strategy that is unproven. There is general interest in strategies that have been tried in similar settings and have detailed data and other information available on impacts to product quality, upfront costs, and costs compared to potential cost-savings over time. The risks involved with investing time and/or money in strategies that are not fully proven and understood came up more frequently in interviews in the US compared to the other two countries.

There were other differences between the three countries regarding sources of information and other support for improving efficiency. First, some supply chain actors in the US had received or were aware of grants or cost-share support from the state or federal government to improve efficiency (e.g., a federal program helped a feedmill purchase new, more efficient equipment). Interviewees in the US stated that these types of programs often require a significant amount of staff time for finding relevant opportunities and preparing applications; another issue was funding levels that have stayed the same while costs have increased, therefore resulting in programs covering a smaller share of the costs. On the other hand, it was common to hear from supply chain actors in Vietnam that they were looking for more support from government agencies. Specifically, many hatchery and grow-out operators would like government agencies to create and implement regional plans that would address water quality issues caused by agricultural operations and other sources of water contamination that are nearby and/or up river. Supply chain actors in Vietnam were also frustrated by a lack of support from universities. Some interviewees described developing and testing their own strategies to address problems at their operations, and their associated frustration that this information was not coming from universities (or not at an adequate level). By contrast, in Norway, many supply chain actors explained that academic researchers were an important source of information that contributed to innovation in the farmed salmon industry.

4 Discussion

Using the FEW nexus as a framework, we collected qualitative data from a variety of seafood supply chain actors across six supply chains that are important for the US seafood supply. Understanding how water and energy are used in these settings, and supply chain actor motivations, barriers, and perspectives regarding efficiency strategies, is critical for improving resource use.

The results indicate that the indirect costs of water use is a priority area for developing efficiency strategies, including instances where water and energy use are coupled. Availability and direct costs of water were not significant concerns across the respondents, but interviewees were aware of indirect costs, including cost of energy, that could be reduced if they were able to reduce the volume of water used. For example, reducing the volume of water used on a pond-based farm could reduce energy used to run pumps, and using less ice in product shipments (e.g., due to improved packing materials that keep products cold) would decrease water and energy used to make ice at processing plants. These strategies, that target coupled use of energy and water instead of areas that involve tradeoffs, could result in less use of water and energy per unit of production and thus lower costs for businesses.

Development and/or adoption of efficiency strategies that address commonalities across multiple supply chains, such as wastewater treatment and preservation technologies, should be prioritized. For example, more efficient and/or cheaper ways to aerate, treat, and/or recirculate water in aquaculture systems are cross-cutting and can impact multiple supply chains. Similarly, innovations in cooling and preservation technologies that reduce the volume of ice used during shipping is relevant across supply chains.

We found numerous differences across production methods and settings. The industry is fractured by geographic and sociopolitical settings, varying priority areas needing innovation due to different stressors, and competition within the industry. The heterogeneity likely results in less investment in and support for identifying, developing, and scaling-up strategies and innovations that would improve efficiencies and lower costs than might be expected considering the overall size of the seafood production industry.

Fisheries research has shown that supply chain actors are an important source of ideas for innovative strategies to solve problems (Jenkins, 2010), and also that substantial government support is needed for many innovations to become commercially viable (Dreyer et al., 2019). These fisheries studies, and the results of the current study, support development and/or strengthening of partnerships between industry, government agencies, and academic researchers focused on identifying or developing innovative solutions and working together to scale-up adoption. The benefit of partnerships, and varying levels of current effectiveness, were brought up by interviewees across supply chains. With the goal of improving resource use across the seafood industry, concerted efforts should extend beyond country borders.

There are limitations of this study. We focused on collecting information that was most salient to the FEW nexus, and many aspects of sustainability of food supply chains and social responsibility are not included in the study, such as holistic ecosystem effects and worker health/wellbeing. In addition, prioritizing strategies based on the greatest potential to reduce resource use or improve cost-effectiveness was beyond the scope of the study. Similarly, the study did not attempt to evaluate the prevalence of various practices. Future research should examine these factors. Also, the research relies on perceptions and recall of interviewees, and, given the number of supply chains and stages studied, the research often included a relatively small sample in specific stages of the different supply chains. Lastly, most interviewees were in management and/or ownership roles, and their perceptions may differ from those of frontline workers.

5 Conclusion

This study contributes to an in-depth understanding of six seafood supply chains, including wild and farmed, and international and domestic supply chains. We characterized the operations of multiple stages in each supply chain using the FEW nexus framework, and the descriptions of trends, resource use, and synergies and tradeoffs provide extensive context that should inform future research, interventions, and policies. The study illustrates the importance of engaging with supply chain actors in order to learn from their expertise and perspectives and to develop practical solutions. The supply chain actors shared firsthand knowledge of their operations and explained which aspects of resource use at the operations they have been working to improve and/or are most interested in addressing. These perspectives are critically important for stakeholders to understand because current perceptions will impact rates of adoption of an intervention. In particular, we found interest among many supply chain actors in reducing water use to lower associated energy and/or water treatment costs, and common resource use issues in multiple seafood supply chains that would benefit from innovations that are scaled-up in multiple settings. Future studies can build on these results by developing inquiries informed by the details we provide on how the FEW nexus describes the supply chain stages, including quantifying resource use and modeling costs and impacts of potential interventions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Johns Hopkins Bloomberg School of Public Health IRB. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because of a low risk of harm to participants.

Author contributions

JF: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. RS: Investigation, Writing – review & editing. TG: Writing – original draft, Writing – review & editing. DL: Conceptualization, Funding acquisition, Investigation, Writing – review & editing. FA: Conceptualization, Funding acquisition, Investigation, Writing – review & editing. MB: Funding acquisition, Investigation, Writing – review & editing. EN: Investigation, Writing

– review & editing. LN: Investigation, Writing – review & editing. LJ: Funding acquisition, Writing – review & editing. JA: Conceptualization, Funding acquisition, Writing – review & editing. RN: Conceptualization, Funding acquisition, Investigation, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1269026/full#supplementary-material

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