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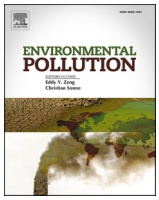
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Review

Characterization of seafood processing wastewater: Processing procedures and physicochemical variability☆

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ABSTRACT

The seafood processing industry produces large volumes of wastewater rich in organic matter, nutrients, and salts, often exceeding legal discharge limits and posing environmental risks. This review introduces a five-stage classification of seafood processing wastewater (SPW), based on key processing operations: initial washings (stage 1), filleting (stage 2), cooking and canning (stage 3), final washings (stage 4), and combined discharge (stage 5). Unlike previous reviews, this structured approach allows for a clearer link between processing steps and pollutant profiles. By adopting this structure, our review addresses a specific gap: the need for a standardized yet detailed framework to understand pollutant load variation across different seafood processing steps. Results show that stage 3 wastewater contain the highest concentrations of BOD, COD, TN, TAN, TP, and oils, followed by stage 2. In contrast, stage 1 and 4 wastewaters carry lower pollutant loads. This categorization enables identification of critical control points and supports the design of stage-specific treatment strategies. The findings highlight the necessity of distinct treatment approaches to improve resource efficiency and reduce environmental impact in seafood processing. This not only improves effectiveness of treatment, but also enables targeted circular economy interventions such as stage-specific recovery and valorisation strategies.

1. Introduction

A large proportion of captured fish is processed prior to onward distribution to retail and catering outlets. Processing includes procedures such as evisceration, filleting, cooking, packing and cleaning. All of these processes generate wastewater. Processing wastewater from fish, shellfish, and other marine products may contain flesh, blood and bones, and is often rich in organic content such as solids, fats, oils, greases, proteins, and microscopic particulate matter (Chowdhury et al., 2009). Consequently, such wastewater has high concentrations of chemical oxygen demand (COD) and biological oxygen demand (BOD) which, if released untreated on surface waters, will have a negative effect on aquatic habitats (Gómez-Sanabria et al., 2020). Besides organic matter, these wastewaters frequently contain nutrients like phosphorus, nitrogen and other minerals, sometimes accompanied by disinfectants and cleaning agents (Muthukumaran and Baskaran, 2013). Because of the complex composition of wastewater, treatment is difficult and necessitates specialised remediation methods optimised for seafood processing wastewater (SPW), prior to release on the environment (Sar et al., 2024).

In the present review, the term *wastewater* refers to the process water generated during the various stages of seafood processing, prior to any form of treatment. *Effluent* is used specifically to describe the treated or untreated discharge leaving the facility or entering receiving environments. The distinction is made to differentiate between internal process flows and external discharges where relevant.

A circular economy approach to wastewater treatment is attractive for the seafood processing industry as waste valorisation can enhance both sustainability and profitability (Cortés et al., 2021). By adopting circular strategies such as reusing water, recovering proteins, oils, minerals and other bioactive compounds, the industry can valorise waste and reduce its ecological footprint. Currently, SPW is managed and treated to minimise its ecological impact and to conserve water. This is typically a major financial expense for the industry. Waste valorisation in accordance with the principles of the Circular Economy (Cooney et al., 2023; Do et al., 2021) can generate new income streams and improve the overall sustainability of seafood processing. Knowledge of

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the physicochemical composition and attributes of processing wastewater is imperative to formulate efficacious treatment approaches and maximise resource recovery. However, the physicochemical composition of wastewater is likely to vary depending on the actual processing treatment. This variability has been poorly characterised in the literature.

The aim of this review is to identify and categorize the main stages of seafood processing and establish the physicochemical characteristics of the associated wastewaters. To achieve that, a systematic review of the literature was performed, to determine 1) the description of the specific seafood processing stage; 2) the physicochemical characteristics of the wastewater for each processing stage, and 3) details concerning storage and/or other treatments. These data will underpin the development of appropriate methods for sustainable and profitable wastewater valorisation.

2. Methods

2.1. Monitoring, gathering and data reviewing

Google Scholar was used to find publications detailing SPW characteristics, and data were recorded using Microsoft Excel spreadsheets. Used search terms were "seafood processing wastewater" and/or "fish processing wastewater". The criteria used for inclusion of publications relate both to the content of the published study and to publication quality, and are detailed below.

i. Publications included sufficient quantitative data on processing procedures and physicochemical, biochemical, and elemental composition of seafood processing wastewater.
ii. The publication included sufficient descriptive data on processing wastewater characteristics of different industrial processing procedures.
iii. The publication was published in the last 13 years (2010 to December 2023).
iv. The publication described original research (i.e. only experimental work).
v. The publication was peer reviewed and published in a scientific journal.
vi. Studies were accessible and published in English.

Publications with insufficiently detailed descriptions of the treatment stage and/or composition of seafood/fish processing wastewater were excluded. Also excluded were studies whereby the wastewater composition referred to a mixed waste stream. Research publications detailing the physicochemical composition of artificial/synthetic seafood processing wastewater, of wastewater from fish/wet markets and of household seafood residues, were also excluded.

The term SPW covers a broad range of wastewaters originating in different socio-economic systems. Diversity relates to the seafood species being processed, the processing techniques and methods, and the quantity of material being processed. In this review, a broad categorization has been established to systematically classify the major processing procedures, as well as the type of seafood (fish and shellfish/crustaceans), as specified in the dataset's categorical data. This approach facilitates the identification and differentiation of wastewaters and their specific characteristics. Along, with the categorical data, descriptive and quantitative physicochemical data were recorded (Table 1). "The category "descriptive data" contains qualitative facts about SPW, including details concerning the wastewater collection point and storage conditions. The sensory assessment of the initial wastewater includes reporting of the presence of blood and fish parts, and smell and colour.

Table 1
Lists of categorical, descriptive, and quantitative data in the data set.

Categorical data	Descriptive data	Quantitative data
• Processing procedure • Seafood species	• Collection point, plus details of facility • Sensory assessment of wastewater • Means of wastewater collection • Storage conditions and duration in facilities • Background information on potential after-use of wastewater	• Physicochemical composition pH, T, BOD, COD, TN, TKN, NO_3-N, NO_2-N, NH_3-N, NH_4-N, TP, PO_4^{3-}, SS, TS, TSS, TDS, VS, VSS, TFS, Salinity, Turbidity, Total Alkalinity, Total Hardness, Conductivity, Colour • Elemental composition Cl, F, Al, Ca, Na, Mg, SO_4^2, Fe, Cr • Biochemical composition Proteins, VFA, O&G

T-Temperature, BOD-Biological Oxygen Demand, COD-Chemical Oxygen Demand, TN-Total Nitrogen, TKN- Total Kjeldahl Nitrogen, NO_3-N -Nitrate, NO_2-N -Nitrite, NH_3-N -Ammoniacal Nitrogen, NH_4-N -Ammonium Nitrogen, TP-Total Phosphorous, PO_4^{3-}-Orthophosphate, SS-Suspended Solids, TS-Total Solids, TSS-Total Suspended Solids, TDS-Total Dissolved Solids, VS-Volatile Solids, VSS-Volatile Suspended Solids, TFS -Total fixed solids, FOG-Fats oils and greases, Cl -Chlorine, F - Fluorine, Al - Aluminum, Ca – Calcium, Na – Sodium, Mg – Magnesium, SO_4 - Sulfate, Fe – Iron, Cr = Chromium, VFA – Volatile Fatty Acids, O&G – Oils and Greases.
Note: This table is based on data extracted from multiple peer reviewed studies included in the systematic review. The following additional peer reviewed studies contributed data to this dataset and are cited here: Álvarez et al., 2023; Amado et al., 2015; Amado et al., 2013; Amado et al., 2014; Amado et al., 2014; Anh et al., 2011; Ayyoub et al., 2022; Carrera et al., 2021; Chaiprapat et al., 2016; Chatzisymeon, 2015; Cheirsilp et al., 2022; Chen et al., 2021; Chowdhury et al., 2009; Correa-Galeote et al., 2021a, 2021b; Corsino et al., 2015; Cristóvão et al., 2012; De Lima et al., 2011; Devasena et al., 2020, 2023; Divya et al., 2015; Do et al., 2021; Dziomba et al., 2013; Fagundes-Klen et al., 2023; Figueroa et al., 2014; Gao et al., 2018; Gamraoui et al., 2023; Gao et al., 2018; Gómez-Sanabria et al., 2020; Grgas et al., 2020; Guimarães et al., 2018; Jamal et al., 2020; Jamieson et al., 2009, 2013; Jayashree et al., 2016; Jayasinghe and Hawboldt, 2013; Jijai et al., 2016; Keluskar et al., 2019; Marcos et al., 2021; Martínez-Montaño et al., 2020; Iosr et al., 2015; Metcalf & Eddy, Inc, 2003; Militon et al., 2015; Mseddi et al., 2013; Ngan et al., 2017; Nguyen et al., 2018; Nouj et al., 2021; Pedrouso et al., 2020; Pinho and Mateus, 2022; Pugazhendi et al., 2020; Roibás-Rozas et al., 2020; Sarvajith and Nancharaiah, 2020; Sillapacharoenkul and Sinbuathong, 2020; Steinke and Barjenbruch, 2010; Thongsai et al., 2021; Tonon et al., 2015; Trivedi et al., 2019; Tsipa et al., 2022; Van Manh et al., 2017; Varadarajan et al., 2020; Vymazal, 2006; Yan et al., 2018; Zappi et al., 2019a; Zulkipli et al., 2021.

2.2. Data editing and statistical analysis

Excel was used for initial analysis of the dataset, and to calculate the arithmetic mean, median, standard deviation, range (min.-max.), and the count of the various quantified variables. Prior to analysis, and where feasible, units were standardised. For example, all physicochemical concentrations were converted to mg/L. Similarly, data for salinity, turbidity and conductivity were converted to g/L, NTU and μS/cm, respectively.

Numbers of publications, detailing the physicochemical characteristics of a particular wastewater treatment stage, varied. Only parameters with four or more independent values were chosen for statistical analysis, using the R statistical environment (R Core Team, 2024; R 4.4.1.). Every parameter for which just three or fewer values were available, was not considered in the analysis. Shapiro-Wilk tests were used to determine normality ($p \leq 0.05$). One-way ANOVA tests were used to compare mean values for normally distributed data between the different processing stages, while Kruskal-Wallis tests were used for non-

normally distributed data. Tukey HSD post hoc tests were employed following application of ANOVAs, with Dunn's test post hoc followed the application of a Kruskal-Wallis, ($\alpha = 0.05$). Outliers were defined as data points more than 10-fold different from the mean were excluded. In cases where the concentration of a parameter was given as a range, the mean concentration was recorded.

3. Results

3.1. Classification and categorization of seafood processing wastewater

A total of 73 peer-reviewed articles on industrial seafood processing wastewater were included in this review. Some of these publications addressed more than one source of industrial seafood wastewater, or more than one processing procedure, in these cases each of these datasets were entered as individual case studies. Among the reviewed studies, 23 articles focused on the processing of fish, while 18 articles examined the processing of shellfish, crustaceans or cephalopods (Fig. S1). Some articles reported on both fish and shellfish wastewater.

In the majority of the reviewed publications the specific type of seafood processed is not explicitly identified. However, fish is more frequently mentioned compared to other categories of seafood. Among the fish species Atlantic salmon, Nile tilapia, tuna, and mackerel are the most commonly referenced, though other species, such as common dolphinfish, Alaska pollock, dogfish, basa fish, and hake, are also mentioned. In the "shellfish, crustaceans, and cephalopods" category, shrimps are the most frequently documented species, followed by cuttlefish. Other species mentioned include American lobster, Jonah crab, snow crab, sea cucumber, octopus, prawn, mussels, squid, and scallops.

Each industry employs distinct techniques and technologies for processing seafood, and these techniques vary depending on factors such as the country, season, market demand, and the specific species being processed. Nevertheless, five broad primary stages of fish processing can be categorized, encapsulating the diversity of processing methods and technologies (Fig. 1).

The categorization reflects distinct stages of processing, separating for instance superficial washings from more invasive steps such as evisceration, while also distinguishing the wastewater from evisceration of raw seafood from cooking wastewater. The resulting categorization was an adaptation of similar, but not identical, classifications found in the literature. Previous reviews (Jamieson et al., 2017; Vallejos et al., 2020) categorized seafood processing wastewater broadly by referring to wastewater streams as "low- or high-strength" or "primary" and "secondary" processing, without linking wastewaters to specific processing operations. Other terms such as "initial stages" and "final stages" also appear in the literature (Silva et al. 2018; Ferraciolli et al., 2018). In contrast, the present review distinguishes the key stages of seafood processing and introduces a detailed five-stage categorization which allows precise description of contaminant composition and supports targeted, stage-specific valorisation strategies. Such granularity is absent in the general categorizations found in earlier literature. Furthermore, we introduce "stage 5″ to reflect the common industry practice of combining all wastewater streams, which is often overlooked in reviews but crucial for the design of treatment strategies. In our review, the wastewaters generated during arrival of harvested fish at the industrial processing plant and the initial processing procedure were classified as the first stage, while all the main processing treatments that occurred before cooking were included in stage 2. All the wastewaters from the cooking methods as well as the canning procedure were classified as stage 3. The wastewater from the final treatment, right before the final product's distribution, together with the cleaning washings of the facility's equipment were classified as stage 4. Stage 5 is not considered a processing stage in the strictest sense, but rather refers to the situation where all wastewaters are gathered for treatment.

More specifically, stage 1 refers to the initial step in which fish and shellfish are transferred to the processing facility from aquaculture farms or fishing activities. During this stage, the seafood undergoes defrosting (thawing) and washing to prepare for subsequent processing stages. Stage 2, identified as the filleting stage, involves processes such as scaling, deheading, gutting, skinning, and pinbone removal. The wastewater generated in this stage is primarily characterized by the presence of blood, viscera, and fish parts. Stage 3 encompasses the boiling, cooking, and smoking of the seafood products, and includes canning, which follows immediately after these processing steps. Stage 4 involves the washing of equipment, as well as the frosting and glazing of the final product. In most facilities, the generated wastewater undergoes primary or partial treatment, such as coagulation/flocculation, aeration, sedimentation, and/or equalization. Some facilities also incorporate secondary treatment, including anaerobic digestion or chlorination. A small number of facilities do not employ any treatment methods. Furthermore, some facilities pool all the SPW-stages. Such cumulative wastewater produced from stages 1 through 4, is categorized as "stage 5." Publications where the source of wastewater is not explicitly identified, but which provide information on physicochemical characteristics, collection and storage methods, or the types of seafood processed, are classified under "No category" (Fig. 1).

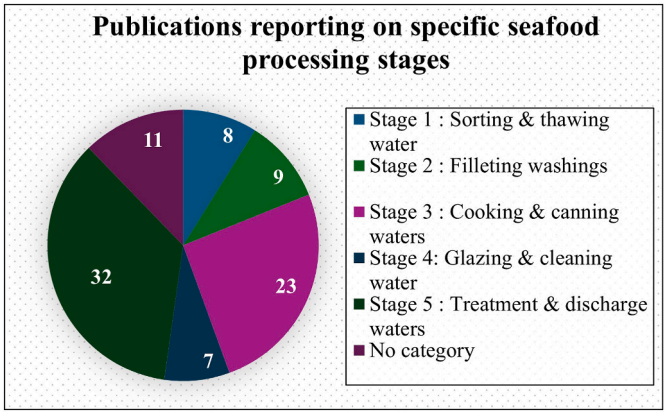


Fig. 1. Categorization of seafood processing stages used in literature review. Numbers in the pie chart refer to number of case studies reporting on a particular stage of wastewater.

3.2. Physicochemical, elemental and biochemical description of the data

The variation in the different physicochemical wastewater

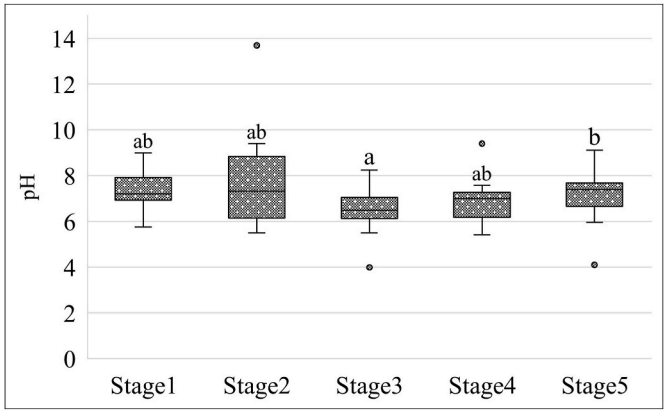


Fig. 2. pH values across the five seafood processing stages. Median, upper and lower quartiles, minimum and maximum values and outliers are shown. Different letters indicate significant differences between stages. Number of data (count) for each stage: stage 1 = 12, stage 2 = 12, stage 3 = 21, stage 4 = 13 and stage 5 = 33.

parameters, between and within the different processing stages, is large (Tables S1, S2, S3). For this reason, only those parameters were included in the analysis for which there were at least four independent replicates. The mean value of each parameter is compared between the different processing stages.

Most publications reported pH values for the wastewater generated during the various processing stages. The overall pH across different stages was between 5.4 and 9.4 (Fig. 2). A comparison of pH values among the stages revealed that the median pH for Stages 1, 2, 4, and 5 ranged from 7.0 to 7.7. In contrast, the median pH for Stage 3 was slightly lower at 6.5, which was significantly lower than the median pH of Stage 5 ($p < 0.05$). Stage 2 exhibited the widest range of pH values, with a maximum recorded pH of 13.7, representing an outlier.

Similar to pH, Chemical Oxygen Demand (COD) values were reported in most of the publications, as were Biochemical Oxygen Demand (BOD) values. The median COD concentrations for stages 1, 2, 4, and 5 ranged from 922 mg/L (Stage 4) to 2253 mg/L (Stage 2) (Fig. 3). Stage 3 exhibited the highest COD concentrations with a median of 4236 mg/L and a maximum of 21,821 mg/L, showing a significant difference with stages 1, 4, and 5. Outlier COD concentrations of approximately 7700 mg/L were recorded for stages 2 and 5 (Fig. 3). Stage 3 also had the highest recorded BOD concentrations, with a median of 1548 mg/L and a maximum of 7060 mg/L. However, no significant differences were observed in BOD concentrations across all stages. An outlier BOD concentration of 19,200 mg/L was noted for stage 3.

Total Nitrogen (TN) and Total Ammoniacal Nitrogen (TAN, i.e. NH_3-N plus NH_4-N) concentrations were recorded (Fig. 4). Stage 3 wastewater contained the highest median TN concentration of 987 mg/L, a value significantly higher than that for stage 4 (TN = 59 mg/L). Stages 1,2 and 5 wastewaters had TN concentrations of 89 mg/L, 435 mg/L and 140 mg/L, respectively, with no significant differences between these stages. Stages 1 and 4 had the lowest TAN concentrations of just 4 mg/L and 8 mg/L, respectively, being significantly lower than the median TAN concentration in stage 3 wastewater (TAN = 89 mg/L). Stages 2 and 5 had median TAN concentrations of 17 mg/L and 63 mg/L respectively, with no significant difference between them and the TAN concentration of the other stages. With a TAN concentration of 3383 mg/L, stage 5 stands out as an outlier, substantially exceeding the mean value (Fig. 4). Stage 3 also had the second highest recorded TAN concentration at 1780 mg/L, which is treated as an outlier.

The most recorded category of solids was Total Suspended Solids (TSS), followed by Total Dissolved Solids (TDS) and less frequently Total Solids (TS). A few publications also recorded Total Volatile Solids (TVS), Volatile Suspended Solids (VSS) and Total Fixed Solids (TFS). For stage 1 and 3 wastewaters there were fewer than four reported values for TS, so no comparisons were made. TS in stage 2, 4 and 5 wastewaters had a median value of 1778 mg/L, 1290 mg/L and 2204 mg/L, respectively, but no significant differences between values were found. Stage 3 wastewater had a median TSS concentration of 1050 mg/L, and a maximum recorded concentration 9404 mg/L (Fig. 5). The median value for stage 3 wastewater is significantly higher than concentrations for stages 1, 4 and 5 (TSS median 324 mg/L, 170 mg/L and 192 mg/L, respectively). No significant difference was found in TSS concentration between stages 2 and 3 (stage 2 TSS = 572 mg/L). Stage 5 was found to have a higher TDS concentration than stage 4, with values of 4213 and 280 mg/L, respectively.

Information about Total Phosphorous (TP) concentrations was only available for stages 3 and 5. No significant differences in concentration were found (Fig. S2). Orthophosphate (PO_4^{3-}) concentrations in stage 2, 3, 4 and 5 wastewaters (for stage 1 wastewater there were fewer than 3

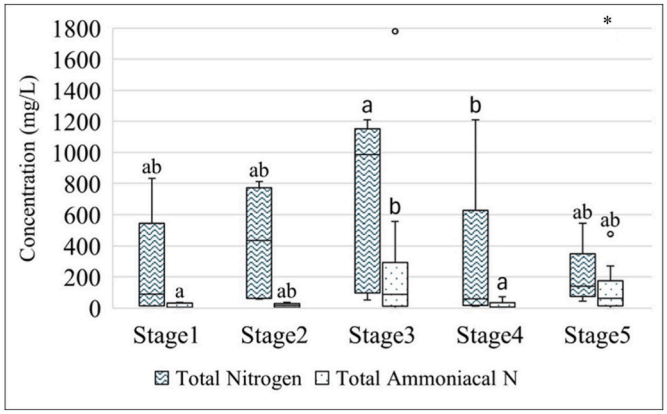


Fig. 4. Total Nitrogen (TN) and Total Ammonia Nitrogen (TAN) concentrations (mg/L) across the five seafood processing stages. Median, upper and lower quartiles, minimum and maximum values and outliers are shown. Different letters indicate significant differences between stages. Number of data (count) for each stage: for TN: Stage 1 = 8, Stage 2 = 5, Stage 3 = 7, Stage 4 = 8 and Stage 5 = 15. For TAN: Stage 1 = 9, Stage 2 = 6, Stage3 = 14, Stage 4 = 9 and Stage 5 = 19. * = outlier value of 3383 mg/L.

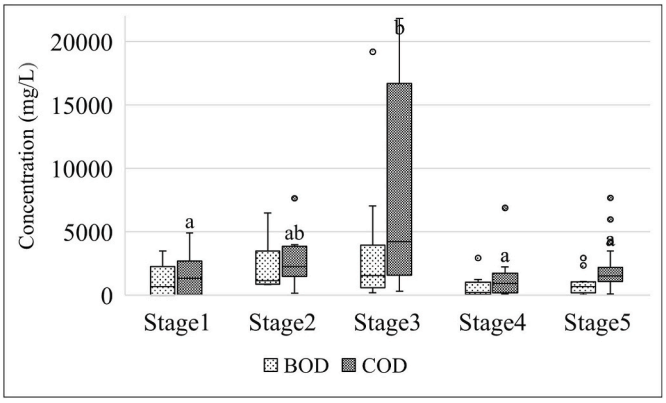


Fig. 3. Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) concentrations (mg/L) across the five seafood processing stages. Median, upper and lower quartiles, minimum and maximum values and outliers are shown. Different letters indicate significant differences between stages for each category of oxygen demand, separately. Number of data (count) for each stage for COD: Stage 1 = 11, stage 2 = 6, stage 3 = 10, stage 4 = 8 and stage 5 = 38; for BOD: Stage 1 = 11, stage 2 = 11, stage 3 = 18, stage 4 = 11 and stage 5 = 21.

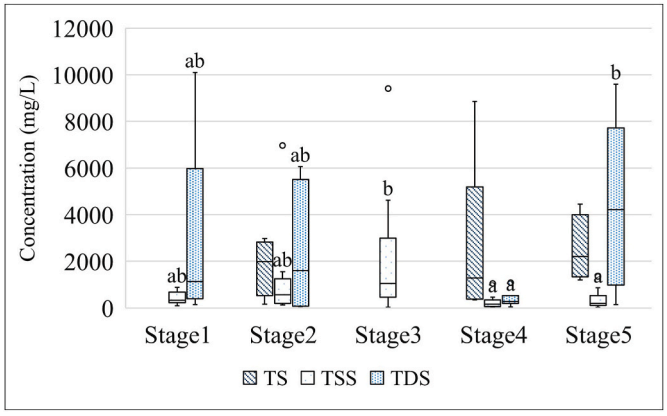


Fig. 5. Total Solid (TS), Total Suspended solid (TSS) and Total Dissolved Solid (TDS) concentrations (mg/L) across the five seafood processing stages. Median, upper and lower quartiles, minimum and maximum values and outliers are shown. Different letters indicate significant differences between stages for each category of solids, separately. Number of data (count) for each stage: for TS: Stage 1 = 3, Stage 2 = 8, Stage 3 = 2, Stage 4 = 5 and Stage 5 = 4. For TSS: Stage 1 = 11, Stage 2 = 9, Stage 3 = 11, Stage 4 = 9 and Stage 5 = 18. For TDS: Stage 1 = 7, Stage 2 = 7, Stage 3 = 2, Stage 4 = 6 and Stage 5 = 6.

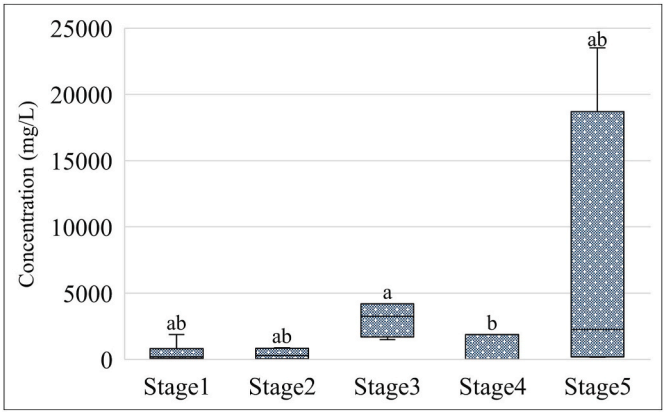


Fig. 6. Chloride (Cl^-) concentrations (mg/L) across the five seafood processing stages. Median, upper and lower quartiles, minimum and maximum values and outliers are shown. Different letters indicate significant differences between stages. Number of data (count) for each stage: Stage 1 = 8, Stage 2 = 6, Stage 3 = 4, Stage 4 = 6 and Stage 5 = 4.

values) were not significantly different even though stage 3 displayed a greater range of concentrations (Stage 3225 mg/L, Stage 2 = 6.9 mg/L, Stage 4 = 1.6 mg/L and Stage 5 = 11.5 mg/L).

The median chloride (Cl^-) concentrations for stage 1, 2, 3, 4, and 5 wastewaters were 202, 301, 3,271, 29, and 2271 mg/L, respectively (Fig. 6).

Stage 3 wastewater contained the highest Cl^- mean concentration, with a value of 3271 mg/L, which was significantly higher than the Cl^- concentration of stage 4 wastewater, which was just 29 mg/L. In stage 5, the maximum Cl^- concentration was 23,500 mg/L, however the median concentration was just 2271 mg/L. Despite the extreme values in stage 5, the median Cl^- concentration did not significantly differ from those observed in the other stages.

Several other parameters frequently reported in the literature, including turbidity, and conductivity, were also evaluated by the present study (Figs. S3 and S4). Median turbidity for stage 1, 4, and 5 wastewaters showed no significant differences, despite stage 5 displaying a higher median concentration and a wider range (Stage 1 = 22 NTU, Stage 4 = 36 NTU, and Stage 5 = 119 NTU) (Fig. S3). The lowest conductivity was found in stage 1 wastewater with a value of 737 μS/cm, while stages 3, 4, and 5, with conductivities of 18,000 μS/cm, 25,650 μS/cm, and 16,685 μS/cm, respectively, exhibited no significant differences among them (Fig. S4).

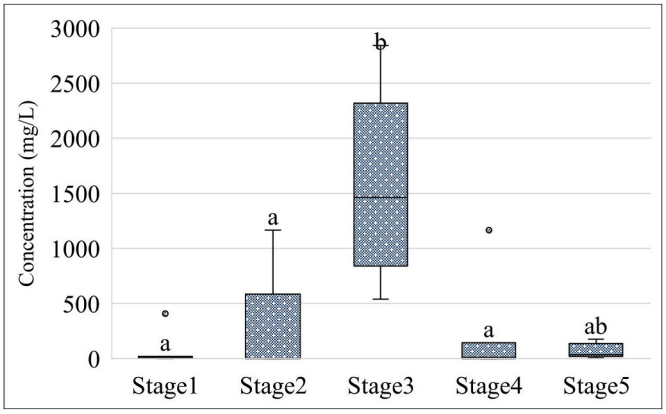


Fig. 7. Oil and grease concentration (mg/L) across the five seafood processing stages. Median, upper and lower quartiles, minimum and maximum values and outliers are shown. Different letters indicate significant differences between stages. Number of data (count) for each stage: Stage 1 = 8, Stage 2 = 5, Stage 3 = 6, Stage 4 = 7 and Stage 5 = 5.

Parameter	Low				High
pH	Stage 3	Stage 4	Stage 1	Stage 2	Stage 5
BOD	Stage 4	Stage 5	Stage 1	Stage 2	Stage 3
COD	Stage 4	Stage 1	Stage 5	Stage 2	Stage 3
TN	Stage 4	Stage 1	Stage 5	Stage 2	Stage 3
TAN		Stage 1	Stage 4	Stage 2	Stage 3
TSS	Stage 4	Stage 5	Stage 1	Stage 2	Stage 3
TS			Stage 2	Stage 4	Stage 5
TDS		Stage 1	Stage 4	Stage 2	Stage 5
NTU	Stage 1	Stage 4	Stage 3	Stage 2	Stage 5
CONDUCTIVITY		Stage 1	Stage 5	Stage 3	Stage 4
PO_4^{3-}		Stage 4	Stage 2	Stage 5	Stage 3
TP				Stage 5	Stage 3
O&G	Stage 2	Stage 1	Stage 4	Stage 5	Stage 3
Cl^-	Stage 4	Stage 1	Stage 2	Stage 5	Stage 3

Fig. 8. Heat map of the compositional characteristics of wastewater from different processing stages. Greener colours (left) show the stages with the lower recorded concentrations while red (right) shows the stages with higher recorded concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Stage 3 wastewater contained the highest median concentration of oils and greases (O&G) at 1464 mg/L (Fig. 7). Although stage 2 displayed a wider concentration range from a minimum recorded concentration of 0.7 mg/L O&G to a maximum recorded concentration of 521 mg/L O&G, its median concentration was the lowest at 1 mg/L, followed by stages 1 at 10.5 mg/L and 4 at 15 mg/L. Stage 5 wastewater had a median O&G concentration of 34 mg/L; however, no significant differences were observed between the O&G concentrations across the stages.

4. Discussion

4.1. SPW composition

Our review reveals that considerable variation exists in the physicochemical composition of SPW, an observation that is consistent with previous studies (Hamatani et al., 2023; Corsino et al., 2015). The seafood processing method, the species of seafood being processed and the technical setup of diverse operations involved in converting raw seafood into consumable products vary widely, and these are likely causes leading to substantial variations in the wastewater composition (Mesquita et al., 2011; Cristóvão et al. 2012; Chen et al., 2023; Hamatani et al., 2023; Sousa et al., 2022).

The variability, along with the elevated concentrations detected, creates challenges for wastewater treatment systems and circular economy-driven valorisation approaches. Therefore, understanding the sources of variation in physicochemical composition of wastewater is essential. Here we explore whether a focus on wastewater from individual processing stages can reduce variability, and therefore facilitate treatment and valorisation.

4.2. Processing stage dependent wastewater composition

Implementation of a successful treatment plan for SPW, traditional or circular, will be facilitated by targeted treatments tailored to the specific characteristics of the waste stream. Here, it is shown that the physicochemical composition of SPW varies depending on the specific processing stage where the wastewater originates.

Stage 3 wastewater contains the highest concentrations of multiple pollutants, including Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Suspended solids (TSS), as well as total phosphorus (TP), orthophosphate (PO_4^{3-}), total nitrogen (TN), total ammonia nitrogen (TAN), and oils and greases (O&G), compared to the other stages (Fig. 8). In agreement, literature shows that stage 3

wastewater from fish and crustacean processing facilities generally exhibit elevated concentrations of nutrients, substantial levels of ammonia nitrogen (NH_3-N) ranging from 29 to 35 mg/L, high total suspended solids (TSS) levels ranging from 0.26 to 125,000 mg/L, increased BOD between 10 and 110,000 mg/L, and COD spanning from 496 to 140,000 mg/L (Jamieson et al., 2017). The source of the high concentrations of pollutants in stage 3 is associated with the cooking and canning processes which generate wastewater that is typically hot and, as a result, rich in dissolved and particulate organic matter, such as fats, proteins, and oils, which leach out from the seafood during heating (Cristóvão et al. 2012). The addition of brines, sauces, oils and other additives during canning further contributes to high concentrations of pollutants in this wastewater (Cortés et al., 2021; Fernández-Ríos et al., 2022; Souli et al., 2023).

Stage 2 wastewater also contained high concentrations of nitrogen and solids, although not as high as those reported for stage 3 (Fig. 8). High concentrations of COD, BOD, TS and TDS are associated with the presence of fish blood, tissues, and residual fats. Some studies have reported particularly high concentrations of these pollutants, for example in squid filleting wastewater COD ranged from 6475 to 6513 mg/L, BOD from 5500 to over 4000 mg/L, total nitrogen (TN) from 760 to 695 mg/L, TSS from 885 to 988 mg/L, and TDS from 6810 to 6000 mg/L (Muthukumaran and Baskaran, 2013). Similarly, Zappi et al. (2019a,b) reported high COD levels in stage 2 wastewater ranging from 2317 to 5383 mg/L, while nitrite and ammonia concentrations ranged from 1.2 to 5.2 mg/L and 8.5–22.8 mg/L, respectively (Zappi et al., 2019a,b). In stage 2 wastewater, the elevated nitrogen content is attributed to the presence of organic matter in the wastewater, while the relatively high TAN content indicates a degree of decomposition, likely associated with guts removed as part of the gutting process. Despite the mean pH for this processing stage wastewater being near neutral, there is considerable variability in pH according to the literature, with values ranging from 5.5 to 13.7 (Ferraciolli et al., 2018; Muthukumaran and Baskaran, 2013).

Stage 1 wastewater, the initial washing, typically has a neutral pH and a moderate chloride concentration (202 mg/L). Due to the washing of fish and shellfish parts, the wastewater exhibits somewhat increased BOD and COD concentrations (700 and 1347 mg/L, respectively) compared to stage 4. Guimarães et al. (2023) have suggested that these elevated values may result from prolonged submersion of fish in water during thawing, which can last up to 24 h (Guimarães et al. 2023). The possible washing away of blood, tissues, and other organic materials is also consistent with the relatively high TN concentration of 89 mg/L, while the low TAN concentration (4 mg/L) suggests that nitrogen is primarily in organic form, which is consistent with minimal microbial degradation occurring in the cold preservation stage. Although the conductivity of stage 1 wastewater (737 μS/cm) indicates a relatively low load of dissolved solids and inorganic materials (possible naturally occurring salts from seawater and sodium chloride brine used in early processing chlorides along with sulphates and phosphates), the TSS and TDS concentrations (324 and 1136 mg/L, respectively) exceed emission limits (Global Seafood Alliance, 2024, https://www.gaalliance.org/). Chatzisymeon (2015) noted that conductivity increases with washing time, rising from an initial value of 50–520 μS/cm after 40 min. This is thought to be primarily due to salts released during the washing process (Chatzisymeon, 2015). The mean turbidity in stage 1 wastewater was found to be relatively low, with recorded values ranging from 0.08 to 43 NTU. Chatzisymeon (2015) observed a substantial increase in turbidity (from 0.079 to 42.7 NTU) within the first minutes of washing, primarily due to the release of solid particles from the shellfish.

Stage 4 involves wastewaters from the freezing and packaging of products ready for the market, as well as washings from equipment. This stage is characterized by the lowest organic load (COD and BOD) compared to all other stages and a low O&G concentration compared to stages 3 and 5, as well as low nitrogen and orthophosphate content. In stage 4 the highest mean conductivity was recorded compared to all other stages, and this is possibly due to the application of chemical cleaning products and/or release of remaining salt-containing residues that are washed away during this stage.

Stage 5 represents pooled wastewater from all processing stages. This stage also includes wastewater that has been partially or fully treated, and in some cases chlorinated and disinfected (Vallejos et al., 2022; Sampaio et al., 2022) which explains the second highest median pH concentration (7.4), and the second highest mean concentration of Cl^-. The O&G concentration was found to be below the legal limits for discharge. Compared to other stages, BOD and COD concentrations as well as the nitrogen and orthophosphate levels, were low. Stage 5 recorded the highest Turbidity and TDS concentrations across all treatment stages, but the TSS mean concentration was lower than at stage's 1, 2 and 3.

4.3. Potential ingredient recovery methods

Stage 3 wastewater contains the highest concentrations of O&G. Fish oils are widely used in nutritional supplements, as they are rich in omega-3 polyunsaturated fatty acids. By focussing oil extraction and purification on stage 3 wastewater, advantage is taken from relatively high concentrations of O&G, increasing yields (Adeoti and Hawboldt, 2014). Demand for fish oil and a well-developed market exists to support such valorisation.

No specific data on protein content were recovered by the present study. However, a high concentration of TN in stage 3 and stage 2 wastewater implies the presence of relatively high concentrations of protein, which can be captured as part of a circular economy approach. Thus, a cascading valorisation can be envisaged whereby first oil, and subsequently protein is extracted from stage 3 wastewater (Ghaly et al., 2013). The remaining residue can then be used for energy valorisation.

Stage 3 and 2 wastewaters contain high concentrations of BOD, COD, and TSS and the energy content of such wastewater can be valorised. Wastewater containing COD concentrations higher than 1500–2000 mg/L are favourable for anaerobic digestion, in the right conditions, as reactors can work on lower temperatures (Metcalf & EddyInc, 2003). Therefore, less energy is consumed, and more methane is produced. As an alternative to anaerobic digestion, the organic compounds in the wastewater (e.g., COD or other substances) can be adsorbed onto activated carbon for subsequent extraction and recovery of high-value compounds such as fatty acids through distillation or solvent extraction, potentially serving as feedstock for chemical or pharmaceutical industries. A third alternative to handle both organic load, as well as nutrients is to cultivate organisms such as algae or yeasts in these highly concentrated wastewaters. This can result in remediated wastewater and valuable biomass for market use, as biofuel or feedstock (Azin et al., 2022; Chen et al., 2023).

Stage 4 and 1 wastewaters contained lower concentrations of pollutants within all stages making them suitable for simpler and more cost-effective ways of treatment. COD concentrations were below 1500 mg/L, meaning that aerobic digestion methods alone can be sufficient for treatment. Alternatively, constructed wetlands or natural systems such as soil absorption systems (Vymazal, 2006) or pond/lagoon systems (Steinmann et al., 2003) can be used for treatment. Harvested wetland plants can be used for biofuel production, composting, animal feed (if suitable species), while nutrient-rich sediments can be used as soil amendments, fertilizers and growing media (Pinho and Mateus, 2022). In particular, algae, yeast and duckweeds (Lemnaceae spp.) can be used to phytoremediate aquaculture wastewaters (Gamraoui et al., 2023; Stejskal et al., 2022). Biomass generated from wetlands, pond/lagoon systems, or environmentally controlled indoor cultivation systems (Coughlan et al., 2022), can be used as biofuel feedstocks (Zhang et al., 2012) but also tend to be nutritionally valuable ingredients for animal feeds due to high crude protein and nutritionally desirable amino acid and fatty acid profiles (Yan et al., 2013; Appenroth et al., 2017).

Given the variability in pollutant concentrations across processing

stages, future research could incorporate Artificial Intelligence (AI) based tools – such as machine learning models – to predict pollutant concentrations across seafood processing stages, supporting real-time treatment decisions and tailored valorisation strategies. Recent studies have demonstrated the potential of such approaches in wastewater quality assessment and dynamic, stage-specific treatment design (Rashidi and Moghaddam, 2021). In turn, while NaCl can be extracted from saline wastewaters generated by the seafood processing industry through various desalination processes (e.g., Hamimed et al., 2022), but given the low economic value of salt as a recoverable product, desalination was not considered as a recovery pathway by the present review. Instead, this review has focused on the valorisation of higher-value compounds, such as proteins and lipids, which are present in greater abundance, currently poorly exploited, and offer more feasible recovery potential for greater system valorisation.

Finally, advanced statistical and mathematical modelling could be used to better assess overall processing performance to gain greater insight of relationships between multiple input variables and desired outputs for improved wastewater remediation and valorisation (e.g., Hedayati Moghaddam et al., 2023).

5. Conclusion and future recommendations

Industrial seafood processing produces substantial volumes of wastewater, with highly variable concentrations of pollutants depending on the specific processing method and species handled at each facility. This review aimed to categorize the industry's processes into four main stages, along with a fifth stage encompassing all the wastewater generated. By identifying the key characteristics of wastewater at each stage and analysing their variability it became evident that treating the wastewater from each stage separately can offer substantial benefits. Such an approach could facilitate the recovery of valuable marketable ingredients and lead to more cost-effective and circular treatment solutions for the industry.

CRediT authorship contribution statement

Alexandra Katsara: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization, Formal analysis, Writing – review & editing. **Neil E. Coughlan:** Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Marcel A.K. Jansen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization, Investigation, Methodology, Project administration, Validation.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126761.

Data availability

Data will be made available on request.

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