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FINAL REPORT

NEW OPPORTUNITIES FOR ABALONE PROCESSING WASTE: PHASE 1

Australian Government
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Cooperative Research Centres Program
END FOOD WASTE COOPERATIVE RESEARCH CENTRE
FRDC Fisheries Research and Development Corporation
Abalone Council Australia Ltd

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Panel Review Statement

End Food Waste CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard. The author(s) confirm(s) that this document has been reviewed and approved by the Project Leader and Industry Partner.

This project has also been evaluated by the End Food Waste CRC publication review panel. These reviewers evaluated its:

- Methodology articulated clearly
- Positioning of findings within the current literature
- Acknowledged compliance with food safety standards
- Conclusions against results
- Relevant human and/or animal ethic approvals obtained

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Table of Contents

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End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

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End Food Waste Cooperative Research Centre is funded through the Australian Government's CRC Program administered by the Department of Science, Industry and Resources.

List of Figures

List of Tables

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Industry Partner Foreword

The Australian abalone industry is internationally recognised for producing a premium, high-value seafood product. At the same time, with up to two-thirds of harvested biomass not entering primary markets, there is a clear opportunity to improve resource utilisation and capture greater value from existing production.

This project, delivered in partnership with Abalone Council Australia (ACA), the End Food Waste CRC, and supported by the Fisheries Research and Development Corporation (FRDC), represents an important step in addressing this opportunity. It provides a comprehensive, industry-informed assessment of abalone processing by-products and identifies practical pathways for their improved utilisation.

A key strength of this work is its grounding in industry realities. The findings reflect the operational, logistical, and regulatory considerations faced across the sector, ensuring that the opportunities identified are both technically credible and commercially relevant.

The report highlights a range of pathways, from near-term applications such as pet food ingredients and functional products, through to longer-term opportunities in nutraceuticals, biomaterials, and sustainable packaging. Collectively, these represent a significant opportunity to enhance industry value, reduce waste, and contribute to broader circular economy objectives.
From an industry perspective, this work provides a strong foundation for the next phase. Realising these opportunities will require continued collaboration between industry, research, and government to support pilot-scale trials and facilitate commercial uptake.
On behalf of Abalone Council Australia, I would like to acknowledge the contribution of the research team and project partners in delivering this work and look forward to seeing these opportunities progressed into practice.

Abalone Council Australia Ltd

Dean Lisson
Chief Executive Officer
Abalone Council Australia (ACA)

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Executive Summary

Australia's wild-harvest abalone industry produces a premium export product; however, conventional processing results in approximately two-thirds of total biomass being classified as non-marketable waste. This includes viscera (~25% of total weight), shell (~33%), and blood (~8%). Historically, these streams have had limited commercial utilisation, representing both an economic inefficiency and a missed opportunity within a circular bioeconomy framework. Increasing national emphasis on resource recovery, waste minimisation, and value-added manufacturing has highlighted the need to transition from disposal-based handling of seafood waste toward higher-value commercial applications.

In response to this challenge, this project was instigated by the Abalone Council of Australia (ACA) to investigate commercialisation options for the traditional waste of Australian abalone processing from the four wild harvest commercial species, namely Blacklip Abalone (*Haliotis rubra rubra*), Brownlip Abalone (*H. rubra conicopora*), Greenlip Abalone (*H. laevigata*), and Roe's abalone (*H. roei*). The work initially focused on the viscera (~25% of total abalone weight) but was later extended with a preliminary investigation of the shell (~33%) and the blood (~8%). The project was supported and complemented by the completion of two higher degree research (HDR) studies. A M. Phil project awarded to Lynne Loo was entitled *"Improving outcomes for shell and shucking by-products in Australian abalone fisheries – A supply chain perspective"*. As well as a PhD project was undertaken by (Alexis) Wing Huen Chung and was titled *"Utilising Australian Wild-Harvested Abalone Viscera for Functional Food Applications: A Translation-Focused Approach"*. Summary data from these theses are included in this Final Report. Furthermore, detailed technical reports and published articles are cited and summarised in this Final Report; complete copies of these various documents can be obtained on request.

The project commenced with a comprehensive assessment of the current status of wild-harvest abalone production, waste volumes, existing disposal or end-use pathways, and relevant regulatory and market conditions, informed by desktop analysis and stakeholder interviews. This summary sought to understand the current status of wild-caught abalone production and the current utilisation or disposal pathways for processing waste. Following a supply chain mapping study was completed at the product format, regional and species level to understand the volumes of waste potentially available for utilisation and the location and current fate of the product. Current and potential end-use options (functional food, nutraceutical, and pet food applications, supported by existing literature on bioactivity) as identified by the current status review and supply chain mapping were then subject to limited theoretical cost benefit analyses and a series of recommendations were completed. Mapping confirmed that approximately two-thirds of abalone biomass is non-marketable waste; this equated to approximately 331 tonnes of viscera produced at a national scale annually, in addition to an unquantified volume of shell and blood. Tasmania generated the largest by-product volumes (319.5t in 2019), followed by SA (267.9t), WA (201.9t), VIC (67.8t), and NSW (21.9t). It was recommended that South Australia was the best option for the development of a collaborative processing facility due to the waste volumes available in the region and the current processing capacity.

The aligned PhD study then investigated the nutritional (amino acids, fatty acids, minerals, etc), compositional (proximate and macro- and micronutrients) and functional bioactivity (antioxidant and anti-inflammatory) potential of multiple individual samples of abalone viscera derived from the four wild-harvest commercial species: Blacklip, Brownlip, Greenlip, and Roe's Abalone. Where possible, samples from the same species were collected from different harvest regions for comparison. The compositional analyses confirmed that abalone viscera are a nutrient-rich waste, characterised by high protein content (55–68% dry basis), balanced essential amino acids, and valuable polyunsaturated fatty acids, including eicosapentaenoic acid (EPA) and docosapentaenoic acid (DPA). Elemental profiling demonstrated the presence of nutritionally beneficial minerals (e.g., Fe, Zn, Mg) but also identified elevated concentrations of cadmium, nickel, chromium, and total arsenic. While inorganic arsenic (the most toxic form) remained within or close to acceptable thresholds, Hazard Index (HI) values above 1 indicated potential safety concerns under conservative

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exposure assumptions. However, interpretation is limited by the absence of established consumption data and validated dietary exposure methodologies for this novel food ingredient. Importantly, the development of the Estimated Daily Upper Limit (EDUL) framework and experimental mitigation strategies, such as short-term boiling with citric acid, demonstrated that heavy metal risks can be effectively managed to support safe consumption.

Optimisation of enzyme hydrolysis of the viscera to enhance bioactivity was then conducted, and enhanced functionality was proven in *in vitro* studies. In these studies, abalone viscera hydrolysates exhibited high intrinsic bioactivity, characterised by elevated sulfated glycosaminoglycans, strong antioxidant potential, and broad-spectrum anti-inflammatory activities through inhibition of COX and LOX pathways. *In vivo* studies, using HaCaT cell model (skin cells); was then attempted, but the cell culture system was not successfully developed (due to challenges in stability and cytotoxicity) within the project timeline to allow robust testing of antioxidant or anti-inflammatory potential in this system.

Based on the viscera work, four putative product/ingredient formats at increasing levels of technological complexity and regulatory compliance requirements were chosen for further theoretical study. These products, in order of complexity, were frozen packaged viscera; air-dried viscera powder; freeze-dried powder; and bioactive hydrolysate. These products were subject to theoretical (desktop) processing flow development, equipment and operational costings, and assessment against regulatory considerations. Potential final product value was also a consideration, as were mandatory regulatory requirements for commercial sale. This work was summarised, including a preliminary cost-benefit analysis for the putative products, and has been provided to ACA and will inform future commercialisation options. Similarly, a summary document was prepared aligned with company requirements for consideration by large pharmaceutical and/or cosmetic/nutraceutical companies for further investigation of abalone waste as a commercial possibility. It is also perhaps noteworthy that an air-dried abalone viscera powder was successfully commercialised for pet food products and supplements during the project, but production and sale were later ceased due to business difficulties.

Characterisation of the abalone shell in conjunction with the Curtin Corrosion Centre (CCC) identified that abalone shell is a high-purity, structurally distinct biomaterial, rich in biocompatible aragonite and possessing excellent thermal stability. These properties support its potential dual valorisation as a natural calcium supplement, functional filler in biopolymer packaging and biomedical materials. This potential was further tested in this project with some preliminary work on supplementing sustainable packaging ingredients with abalone shell to assess improved functionality of the packaging, including conducting comparative simulated shelf-life studies with Atlantic Salmon (*Salmo salar*) mince.

In some further development work with the CCC, a novel green process for separating high purity aragonite from abalone shell, intended for biomedical applications, was investigated. The method may also enable co-processing with other shell waste streams to improve scalability and commercial viability. Preliminary results were promising, and the results of this work are now being discussed with stakeholders for potential commercialisation.

While preliminary, proximate, nutritional and functional characterisation of abalone blood was investigated. Initial anti-microbial activity was also tested. Further work will be contingent on developing robust procedures for collecting and storing the blood, as it was found to be unstable and highly sensitive to handling, consistent with the properties of other marine blood products used for biomedical applications.

During the project, there was ongoing extension and communication of the results to multiple stakeholders by a variety of delivery mechanisms. These mechanisms included the two HDR theses, academic papers, and multiple industry technical reports, presentations and newsletters. Eight research and internship students also worked on specific aspects of the project, and their research reports can also be provided as outcomes on request.

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A series of specific targeted recommendations and next steps have been developed and are articulated in the detailed report, and a potential Phase 2 project is based on the commercialisation of the opportunities informed by and highlighted in this project. Hence, the overarching recommendations of this report can be summarised as follows:

- Recommendation 1*:* Assess the technical and economic feasibility of pilot-scale commercialisation of viscera and/or shell ingredient opportunities identified in Phase 1 by installation and evaluation of equipment in at least two abalone processing operations.
- Recommendation 2: Undertake further industry trials to maximise yield and product value on commercialisation questions identified in Phase 1 (e.g., functionality of defatted product hydrolysis; heavy metal amelioration; low temperature sterilisation techniques).

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1. Introduction & Project Background

The Australian wild-caught abalone industry is a globally significant sector, contributing approximately $300AUD million annually through the harvesting of four commercially important species: Blacklip Abalone (*Haliotis rubra rubra*), Brownlip Abalone (*H. rubra conicopora*), Greenlip Abalone (*H. laevigata*), and Roe's Abalone (*H. roei*) (ACA, 2020). Despite this economic contribution, the industry faces mounting pressures from reduced catch quotas, climate variability, and disease recovery (FAO, 2016, Loo, 2023). These challenges have led to a decline in production volumes, amplifying the need to optimise resource utilisation and capture greater value from the existing harvest rather than relying on increased output.

A critical issue facing the sector is the underutilisation of processing waste. Current estimates suggest that up to 66% of the abalone biomass is discarded, consisting primarily of shells (33%), viscera (25%), and blood (8%) (Je et al., 2015, Suleria et al., 2017, Chung et al., 2024a). Historically considered waste, these streams present opportunities for valorisation into higher-value applications. Previous studies, as well as early commercial initiatives, indicate that abalone waste, whilst currently generally disposed at sea or on land, holds promise for use in nutraceuticals, functional foods, pharmaceuticals, pet food supplements, biomaterials, and environmental products. However, the potential of this waste has not yet been systematically investigated at scale within the Australian context, leaving potentially significant economic and sustainability opportunities unrealised.

The industry's underlying need is therefore twofold: to reduce food loss and waste while simultaneously maximising the economic and social benefits of existing resources. Aligning with Australia's National Food Waste Strategy and the United Nations Sustainable Development Goal (SDG) 12.3 (UN, 2024), this project aims to explore abalone waste upcycling pathways that both reduce waste and generate new streams of revenue, jobs, and sustainability outcomes. Specifically, the project focuses on mapping wild-caught abalone supply chains, quantifying waste volumes, assessing biochemical composition, and identifying valorisation pathways for abalone viscera, shell, and blood.

Early scoping has indicated strong industry interest in pragmatic applications such as pet food supplementation, alongside more ambitious long-term opportunities, including nutraceutical and pharmaceutical development. By adopting an interdisciplinary approach that integrates biological and social sciences, this project seeks not only to identify viable technological solutions but also to address the regulatory, market, and stakeholder barriers that have historically limited implementation. In doing so, the project aims to create actionable strategies that deliver measurable reductions in food waste, enhanced industry profitability, new employment opportunities, and improved sustainability outcomes.

2. Aim and Objectives

This project was instigated and supported by the ACA who represent the Australian wild harvest abalone sector.

The aim of this project was to map and utilise abalone processing waste streams to identify and develop viable value-adding opportunities that contribute to industry sustainability and profitability while reducing food loss.

The specific objectives were to:

1. Investigate (through literature review, commercial review, and consultation) the status of wild abalone waste products in Australia, including existing outcomes, barriers, opportunities, pricing, and volumes in both commercial production and research contexts.
2. Map wild-caught abalone waste streams (for all four Australian commercial abalone species) across domestic and export supply chains to quantify volumes, formats, locations, and quality.

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3. Quantify the nutritional and biochemical composition of viscera (untreated) waste components in all four commercial species.
4. Assess the therapeutic and functional characteristics of viscera (untreated and treated) from all four commercial species.
5. Develop an informed statement, underpinned by scientific rigour, of any visceral characteristics with potential therapeutic or functional food application.
6. Evaluate the use of viscera as a holistic therapeutic/functional food agent or in pet food, as well as other outcomes identified by ACA members, for technical, operational, logistical, and economic viability.
7. Where supported by industry partners, undertake commercialisation activities for end-product outcomes deemed viable.

3. Methodology – Overall Framework

The project methodology was structured in five progressive stages to ensure systematic identification, evaluation, and development of abalone waste valorisation opportunities.

1. **Status Review**
   A desktop study, supported by literature reviews, market analysis, and industry consultation, was conducted to document the status of abalone waste utilisation. This included assessment of past and ongoing research, existing processing practices, product formats, and potential barriers/opportunities for uptake.
2. **Supply Chain Mapping and Preliminary Analyses**
   Abalone waste streams (viscera, blood, shell) were mapped across all major species and fisheries, covering both domestic and export markets. Mapping captured quantities, forms, quality, and points of waste generation. Representative viscera and blood samples were collected for proximate and compositional analysis, with food safety testing undertaken by National Association of Testing Authorities (NATA)-accredited laboratories.
3. **Assessment of Valorisation Pathways**
   Based on stakeholder interests and analytical results, targeted valorisation options were explored, with a focus on:
   - Pet food supplementation (powdered viscera products).
   - Human nutraceuticals/functional food applications (hydrolysates and dried powders).
   - Shell applications (calcium carbonate, aragonite, and related additives).

   Multiple potential pathways were investigated for technical feasibility, nutritional/functional potential, and alignment with industry and consumer context.
4. **Feasibility and Stop/Go Analysis**

   A preliminary process flow, costings and technical feasibility analysis were undertaken to stage compared production costs, market potential, and logistical considerations to inform stop/go decisions on each valorisation stream.
5. **Knowledge Transfer**

   For valorisation options deemed viable, recommendations for commercialisation trials were developed in consultation with industry partners. Where appropriate, co-funding was sought from ACA members to support larger-scale activities. Parallel to this, training and knowledge transfer activities were planned, including postgraduate student training and industry workshops to disseminate findings and build capacity.

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This structured methodology ensures that each stage of the project, from mapping to feasibility to investigation of commercialisation feasibility, is directly tied to industry relevance, maximises utilisation of abalone waste, and supports broader goals of sustainability, profitability, and circular economy outcomes.

It is noteworthy that a series of technical reports and peer reviewed journal articles referred to in this final report were submitted to the CRC with this report and will be archived in the CRC database under their standard policies. They have not been appended here due to length constraints but remain accessible on specific request via the CRC.

4. Current Status Report

Full details of the current status report can be found in Loo (2023), and key results are summarised below.

4.1 Method

The status of abalone waste streams and outcomes was investigated through a desktop review aligned with a qualitative exploratory study (Curtin HRE2021-0714) using semi-structured interviews with key stakeholders in the Australian abalone industry. Participants included quota owners, processors, and other stakeholders across major producing states. Stratified purposive sampling and snowballing were applied to ensure broad representation. Interviews were transcribed, coded, and thematically analysed (NVivo) to identify recurring patterns regarding waste management, commercial outcomes, barriers, and opportunities. Findings were supported by a desktop review of government reports, industry data, and technical literature, ensuring triangulation of perspectives.

4.2 Results

4.2.1 Waste Generation & Streams

Stakeholders confirmed that only ~33% of abalone biomass is marketable, primarily the meat portion, leaving shells (53–75%), viscera (24–45%), and blood (<15%) as waste streams. Whilst some storage of frozen viscera was occurring, disposal was primarily at sea or landfill, incurring costs and regulatory burdens.

4.2.2 Current Commercial Uses

Few valorisation practices exist domestically. Stakeholders cited condiment products, artisanal sauces, and experimental uses in beverages and pharmaceutical products (Loo, 2023). Outside Australia, Asian markets demonstrate wider use of viscera (e.g., fermented dishes).

4.2.3 Barriers Identified

- High cost and logistics of separating, storing, and transporting waste.
- Regulatory uncertainty around food safety and processing approvals.
- Limited consumer awareness and acceptance of viscera-based products.
- Fragmented supply chain with variable waste volumes across states.

4.2.4 Opportunities Identified

- Potential for functional food, nutraceutical, and pet food applications, supported by existing literature on bioactivity.
- Alignment with sustainability goals (SDG 12.3) (UN, 2024).
- Niche export markets with demand for “natural” marine-based products.

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4.2.5 Stakeholder Perspectives

- Processors and quota owners expressed interest in higher-value utilisation, but emphasised the need for low-barrier, practical, and cost-effective solutions. There was limited appetite for highly technical, capital-intensive processes.

4.3 Discussion

Loo's findings demonstrate a clear disconnect between scientific evidence on abalone viscera's functional potential and real-world commercial opportunity. Industry participants recognised both the environmental burden and economic inefficiency of current disposal practices, yet systemic and behavioural barriers prevent upcycling. Economic costs of transport, variable volumes, and regulatory ambiguity reduce feasibility. Stakeholders strongly favoured pragmatic solutions with immediate feasibility, such as crude applications (e.g., pet food, supplements), while acknowledging the potential for longer-term innovation. Importantly, the research highlights that success depends on integrating stakeholder perspectives with technical feasibility, not purely laboratory-driven innovations.

4.4 Conclusion

The investigation established that while abalone waste streams represent significant untapped biomass (up to two-thirds of the volume of wild-caught abalone) with demonstrated bioactive potential, their utilisation in Australia remains negligible. Current practices result in both economic losses and environmental impacts. However, there is a strong industry appetite for feasible valorisation strategies, particularly those aligned with existing infrastructure, consumer expectations, and sustainability imperatives.

4.5 Recommendations and Next Steps

- Develop short-term crude usage applications (e.g., pet food, feed, crude ingredient) that align with stakeholder priorities.
- Conduct targeted biochemical and safety studies to build the evidence base for functional food/nutraceutical claims.
- Map supply chain logistics to address variability and identify aggregation opportunities.
- Investigate and design laboratory studies in accordance with the requirements for novel food approval and relevant safety benchmarks.
- Design laboratory-scale products aligned with the expectations of ACA members, prioritising low technical barriers (i.e., crude or minimally processed products)
- Pursue long-term innovation (e.g., hydrolysates, bioactive isolation) only once baseline markets and feasibility are established.

5. Supply Chain Mapping

All details of this session can be found in Loo (2023) and key results are summarised below.

5.1 Method

Supply chain mapping was undertaken through a combination of secondary data analysis and stakeholder consultation. Literature and government sources provided baseline figures on catch volumes, quotas, and processing practices, while semi-structured interviews (Curtin HRE2021-0714) with stakeholders across five states (SA, WA, TAS, VIC, NSW) captured current on-the-ground realities. Mass flow analysis (MFA) was applied to quantify volumes of waste (shell, viscera, blood) relative to landed catch, using the Food Loss and Waste (FLW) Standard methodology. Mapping incorporated differences in processing practices across states,

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especially the distinction between on-board shucking (common in SA and WA) and on-land processing (TAS, VIC), which directly influences the quantity and traceability of waste generated.

5.2 Result

5.2.1 Volumes

MFA confirmed that approximately two-thirds of abalone biomass is non-marketable waste. At the national scale, recent estimates suggest ~331 tonnes of viscera are produced annually, in addition to considerable volumes of shell and blood. Tasmania generated the largest waste volumes (319.5t in 2019), followed by SA (267.9t), WA (201.9t), VIC (67.8t), and NSW (21.9t).

5.2.2 Processing Practices

Notwithstanding the live domestic and export markets, where domestic processing waste is not produced, there are two primary processing practices employed across the four wild abalone fishing jurisdictions. These practices generate their own waste streams:

- SA & WA: Predominantly on-board shucking, with viscera generally discarded at sea to reduce handling and storage costs.
- TAS & VIC: Land-based processing, where viscera and blood are stored and more often diverted to “other uses” such as compost, pet food, or condiments.

5.2.3 Quality and Form

Viscera quality varies by processing context. On-board shucked viscera have higher exposure to seawater and degradation, while land-processed viscera are more suitable for value-adding.

5.2.4 Current Uses

Shells are exported for decorative or medicinal purposes; viscera are occasionally directed into condiments, pet food, or nutraceutical trials; blood is largely discarded.

5.3 Discussion

The mapping revealed strong regional variation in waste generation and management. States with on-board shucking practices (SA, WA) contribute disproportionately to discard volumes, reflecting logistical convenience but also the greatest opportunity for improvement. Conversely, TAS and VIC demonstrate that on-land processing enables higher recovery and redirection into secondary uses.

A critical finding is that while shell constitutes the largest proportion of waste (~33%), viscera (~25%) and blood (~8%) are of higher value for nutritional or functional valorisation. Yet, supply chain fragmentation and inconsistent data reporting create barriers to scaling recovery efforts. The results also highlight that earlier national estimates (FRDC 2013-711.40) likely overstated true discard volumes, as they did not fully account for existing low value uses (e.g., composting, local disposal, reuse, or secondary processing pathways). This distinction is important when assessing realistic feedstock availability for commercial development.

5.4 Conclusion

The supply chain mapping confirms that approximately 66% of abalone biomass is non-marketable product, with significant portions underutilised or discarded. Waste management varies by state, with SA and WA representing the largest untapped opportunities due to high discard rates. MFA provides a baseline for prioritising interventions, but quality and logistical factors must be addressed for effective valorisation.

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5.5 Recommendations and Next Steps

- Target SA and WA for intervention pilots, where the largest discard volumes occur due to at-sea shucking.
- Promote on-land processing models to improve waste quality and recovery potential.
- Develop zone-specific supply chain maps that incorporate not just volume but also quality attributes of waste.
- Standardise data collection across fisheries to reduce reporting gaps and enable benchmarking.
- Engage industry cooperatives to pool waste streams and reduce logistical costs for downstream valorisation.

6. Preliminary Proximate Analysis

All details of this section can be found in the following documents (Chung, 2025, Chung et al., 2024a, Chung et al., 2025a, Chung et al., 2025b, Chung et al., 2024b, Chung et al., 2024c). Results are summarised below.

6.1 Method

Proximate analyses of three abalone waste streams (shell, blood, and viscera) from all four commercial abalone species were conducted following AOAC (1995) standard methodologies: 935.29 (moisture content), 970.05 (crude protein content), 945.16 (crude fat content), 942.05 (crude ash content), and 2020.07 (crude carbohydrate content). Full details of procedures and analytical protocols are provided in Chung et al. (2024a).

Quantification of essential and trace elements across all three waste streams, including potassium (K), sodium (Na), phosphorus (P), magnesium (Mg), calcium (Ca), iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), total arsenic (As), inorganic arsenic (iAs), and mercury (Hg), was undertaken using a combination of Microwave Plasma Atomic Emission Spectroscopy (MP-AES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and Cold Vapour Atomic Fluorescence Spectroscopy (CV-AFS). Hg, As and iAS determination were conducted by the National Measurement Institute (NMI). To assess potential health risks associated with human consumption, results were compared with relevant food legislation and evaluated using USEPA (2000) Hazard Index (HI) model, alongside a modified Estimated Daily Upper Limit (EDUL) algorithm. Full methodological details are reported in Chung et al. (2024c) and Chung et al. (2024b).

Amino acid profiling of abalone viscera was performed by the Australian Proteome Analysis Facility (APAF) using Ultra-Performance Liquid Chromatography (UPLC) in accordance with standard operating procedures AAA-001, AAA-002, and AAA-003 (APAF, 2022). Full experimental details are available in Chung et al. (2024a)

Fatty acid profiles of viscera were subsequently determined using Gas Chromatography Coupled With Flame Ionisation Detection (GC-FID) by the Department of Primary Industries and Regional Development, Diagnostics and Laboratory Services (DPIRD), supported by the Western Australian State Government. Experimental details are documented in Chung et al. (2024a).

For research related to viscera, four commercially significant species were included: Blacklip Abalone (*Haliotis rubra rubra*), Brownlip Abalone (*Haliotis rubra conicopora*), Greenlip Abalone (*Haliotis laevigata*), and Roe's Abalone (*Haliotis roei*). A total of 11 representative visceral samples were collected and analysed. Complementary studies were undertaken on other waste streams, with the shell study focusing on Greenlip Abalone and the blood study drawing on samples from Roe's and Blacklip Abalone. Further sample details can be found in Chung et al. (2024a).

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6.2 Viscera

6.2.1 Results & Discussion

6.2.1.1 Nutritional Characteristics

For the full project details, including results and a more in-depth discussion, refer to Chung et al. (2024a).

The proximate composition of abalone viscera across the four major Australian wild-caught species, Roe's (*Haliotis roei*), Greenlip (*H. laevigata*), Brownlip (*H. rubra conicopora*), and Blacklip (*H. rubra rubra*), showed notable interspecies and location-driven variability, yet consistent overall nutrient trends. Moisture levels ranged from 72.96–79.97%, confirming that viscera are likely to be highly perishable and require immediate stabilisation post-harvest. On a dry weight basis, protein dominated the composition (55.82–68.04%), positioning viscera as a protein-rich waste suitable for conversion into functional or nutritional products. Carbohydrate levels were more variable (9.96–28.82%), which may reflect differences in polysaccharide fractions, some of which have been associated with bioactive potential in marine organisms. Ash content was also relatively high (10.02–16.75%) compared to Asian abalone species such as Pacific abalone (*Haliotis discus hannai*) and variously coloured abalone (*Haliotis diversicolor* Reeve) (8.3–12.98%), likely reflecting mineral-rich Australian coastal environments and macroalgal diets. Although lipids represented the smallest macronutrient fraction (3.12–13.37%), their unique fatty acid composition warranted further analysis.

The amino acid profiling confirmed viscera as a valuable source of nutritionally essential amino acids (EAAs), which accounted for 35–42% of the total amino acid pool. Glutamic acid and aspartic acid were the most abundant, together exceeding 20% of the total profile. This high concentration of umami-associated amino acids supports potential flavour-enhancing applications in food systems. Among the EAAs, leucine, lysine, and valine were especially abundant, contributing to EAAI values indicative of good-quality protein. These findings reinforce the nutritional potential of viscera-derived protein in functional food and feed contexts.

Fatty acid analysis highlighted a lipid profile rich in Polyunsaturated Fatty Acids (PUFAs, 35–48%), with consistent detection of Eicosapentaenoic Acid (EPA, C20:5n-3) and Docosapentaenoic Acid (DPA, C22:5n-3), though Docosahexaenoic Acid (DHA, C22:6n-3) was absent. This absence is unusual compared to other marine resources but underscores a unique fatty acid fingerprint for abalone viscera. The relatively high DPA content is particularly noteworthy given the scarcity of natural, high-dosage DPA sources, suggesting a potential niche application in nutraceuticals. Saturated Fatty Acids (SFAs) accounted for 25–33% and Monounsaturated Fatty Acids (MUFAs) for 20–28%, producing a favourable PUFA/SFA ratio. Such ratios, coupled with the presence of omega-3 fatty acids, support the potential of abalone viscera oils in human health applications, pet nutrition, and as sustainable marine omega-3 alternatives.

Collectively, these findings demonstrate that abalone viscera are nutritionally dense, with high-value biochemical components spanning protein, amino acids, fatty acids, and potentially functional polysaccharides. The interspecies and location-related variability observed highlights the challenge associated with standardising viscera-derived products, but also presents opportunities for selective targeting of species or processing systems to maximise functional benefits. Notably, the distinctive, high levels of DPA may provide a differentiating feature for abalone-derived products in a growing omega-3 market.

6.2.1.2 Heavy Metal Safety

Full details of the content discussed below are provided in Chung et al. (2024c).

Elemental analysis of abalone viscera across multiple species and harvest locations revealed significant variation in both macro-mineral and trace element concentrations. Na and P were consistently the most abundant macro-minerals, followed by K and Mg, reflecting the dietary influence of macroalgae and the osmoconforming physiology of abalone. Ca content varied dramatically, up to

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~30-fold across samples, likely reflecting both species- and location-specific dietary differences. Such variability highlights the need for standardised processing and blending approaches if viscera are to be commercialised as a consistent raw material input.

Trace element analysis confirmed the presence of Fe and Zn at nutritionally beneficial levels but also identified elevated concentrations of Cd, Ni, Cr, Cu, and As, particularly in total arsenic, which exceeded international regulatory limits in most samples. However, results suggested that the majority of arsenic was likely present in benign organic forms (arsenosugars and arsenobetaine), with iAs remaining within or close to acceptable limits in most cases. Hg and Pb were detected at very low levels and did not exceed legislative thresholds.

Health risk assessment using the HI yields values >1 in most viscera samples under conservative exposure scenarios, suggesting potential concern if viscera were consumed as a full seafood replacement under Australian dietary guidelines of 2 serves per week (NHMRC, 2013). However, this interpretation was likely an overestimation, as abalone viscera are unlikely to be consumed in such high daily volumes. A refined assessment, EDUL adapting the concept of Upper Limit (UL) from human nutritional science, demonstrated that viscera could be safely consumed even at quantities aligned with typical molluscan shellfish intake (10–75 g/week), positioning it as safe under realistic consumption scenarios, even when all detected heavy metals were conservatively assumed to be present in their most toxic forms. Importantly, processing interventions such as short duration boiling with citric acid, reduced HI by up to 34%, validating that simple, low-cost treatments can effectively mitigate heavy metal risk while also improving overall product safety (e.g. pet food safety) and shelf-life.

Statistical analyses (regression and PCA) revealed that heavy metal accumulation was more strongly influenced by location than by species, suggesting that extrinsic environmental factors, such as local water chemistry, algal composition, and potential anthropogenic contamination, play a greater role than genetic or physiological differences between abalone species. This finding supports the feasibility of multi-species waste pooling and centralised processing, provided that location-dependent variations are accounted for through blending, quality control, or processing interventions.

Overall, the results indicate that abalone viscera, despite containing elevated levels of some trace metals, can be safely valorised into functional food, nutraceutical, or pet food applications when appropriate processing, monitoring, and safety standards are applied. These findings also highlight the importance of transparent safety evaluation and consumer communication, as consumer perception of safety has been identified as a critical determinant for the commercial success of upcycled foods.

6.2.2 Conclusion

The compositional analyses confirmed that abalone viscera are a nutrient-rich waste, characterised by high protein content (55–68% dry basis), balanced essential amino acids, and valuable polyunsaturated fatty acids, including EPA and DPA. These attributes position viscera as a promising raw material for functional foods, nutraceuticals, and high-value feed supplements. However, proximate composition also revealed substantial interspecies and inter-location variability, which presents both an opportunity for targeted valorisation and a challenge for product consistency if mixing of product occurs.

Elemental profiling demonstrated the presence of nutritionally beneficial minerals (e.g., Fe, Zn, Mg) but also identified elevated concentrations of cadmium, nickel, chromium, and total arsenic. While inorganic arsenic (the most toxic form) remained within or close to acceptable thresholds, HI values above 1 indicated potential safety concerns if viscera were consumed in large, unrealistic amounts, utilising the conventional worst-case exposure assumption. Importantly, the development of the EDUL framework and experimental mitigation strategies, such as short-term boiling with citric acid, demonstrated that heavy metal risks can be effectively managed to support safe consumption.

Taken together, the findings indicate that abalone viscera represent a viable resource for near-term crude usage (e.g., powders for pet food or functional whole food supplements) and longer-term hydrolysate applications. However, commercialisation must

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address three critical factors: (i) standardisation of composition across species and locations, (ii) routine safety monitoring and application of simple processing interventions to reduce heavy metal loads, and (iii) consumer communication regarding safety and nutritional benefits to build market confidence.

6.2.3 Recommendations and Next Steps

- Scale-up and refine simple, low-cost interventions (e.g., thermal–chelating treatments) to consistently reduce heavy metal and sodium concentrations, ensuring product safety and compliance with both human and pet.
- Refine short-term crude usage application, e.g. develop blending strategies and quality control frameworks to mitigate species- and location-based variability, while addressing toxicity risks to support reliable product formulation.
- Explore and trial long-term transformed innovation of abalone viscera (e.g., hydrolysates, bioactive isolation).
- Continue safety assessments following FSANZ and relevant international standards, and formally present nutritional and safety data to the Advisory Committee on Novel Foods (ACNF) to clarify requirements for approval of abalone viscera as a human food source.
- Initiate early-stage product trials in collaboration with ACA members and industry partners to evaluate technical and economic feasibility, creating evidence-based pathways for investment and scaling.

6.3 Shell

6.3.1 Results & Discussion

Full details available in Chung et al. (2024b).

The proximate composition of abalone shell confirmed its identity as a mineral-rich waste, with ash content consistently exceeding 95% of dry weight. Calcium was the dominant element, with concentrations above 380,000mg/kg, aligning with its classification as a calcium carbonate ($CaCO_3$)-based material. Magnesium, sodium, and phosphorus were also detected at lower but nutritionally relevant levels, consistent with reports from other molluscan shells. These findings establish abalone shell as an abundant, natural source of dietary calcium, comparable in mineral density to commercial calcium supplements derived from oyster and cockle shells.

Cadmium levels (11–13mg/kg) were higher than desirable for direct food applications. This highlights the importance of targeted safety monitoring and the potential need for refining or blending strategies to ensure compliance with international standards.

Despite these safety considerations, the strong nutritional value of abalone shell lies in its calcium content, which exists in a form with high bioavailability compared with inorganic sources commonly used in existing calcium supplement, as well as in consumer-driven preference for “natural” calcium supplements over synthetic or mined alternatives. This positions abalone shell as a competitive raw material for nutraceutical formulations, with added potential to appeal to markets prioritising sustainable and circular economy practices.

6.3.2 Conclusion

Abalone shell is nutritionally characterised by exceptionally high calcium content (>95% ash, dominated by calcium carbonate), positioning it as a valuable natural source of dietary calcium with strong relevance to nutraceutical and functional food applications. Its mineral profile is broadly comparable to other molluscan shells already commercialised as supplements, providing both nutritional efficacy and consumer appeal for “natural” calcium products. However, elevated cadmium levels present a safety constraint, particularly for children, requiring mitigation through refining, blending, or targeted regulatory compliance strategies. Overall, abalone shell represents a promising near-term valorisation stream for sustainable calcium supplementation, provided safety challenges are adequately addressed.

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6.3.3 Recommendations and Next Steps

- Refine short-term crude usage application, e.g. develop low-cost refining and purification methods to reduce cadmium and ensure compliance with FSANZ and Codex safety standards; Investigate blending with low-contaminant calcium sources to maintain bioavailability and enable diverse product formats.
- Prepare an informed statement aligned with FSANZ Schedule 4 nutrient claims and submit a technical dossier to ACNF if required by industry partner.
- Conduct market testing to assess consumer preference for natural marine calcium and highlight sustainability credentials.
- Partner with ACA members for pilot trials and evaluate techno-economic feasibility for scaling to regional hubs.
- Explore and trial long-term transformed innovation of abalone shell (e.g. packaging, wastewater treatment, biomedical usage).

6.4 Blood

Results of the compositional analyses and elemental profiling are presented in Appendix B (**Error! Reference source not found.** and **Error! Reference source not found.**).

6.4.1 Results & Discussion

The proximate composition of abalone blood across species indicated that it contains approximately 5% dry mass, with ash as the predominant fraction, followed by protein. This composition aligns with findings reported for hemolymph in other marine invertebrates (Floreto et al., 2000, Machałowski and Jesionowski, 2021). The relatively high ash content is characteristic of abalone physiology, as their hemolymph maintains near-equivalent ion concentrations to the surrounding seawater environment (Gao et al., 2017, Özden and Erkan, 2011). From a valorisation perspective, the high sodium concentration presents both challenges and opportunities. In whole dried or freeze-dried form, elevated sodium levels may limit applications in pet food or topical products due to potential health and formulation concerns (Chandler, 2008, Chattopadhyay et al., 2023). However, given that most sodium is present as free ions, separation from the liquid fraction, where these ions are concentrated, could be achieved using well-established biomedical separation techniques such as centrifugation, analogous to blood cell isolation methods, allowing the recovery of hemocyanin, which represents up to 90% of haemolymph protein (Machałowski and Jesionowski, 2021, Dalili et al., 2019).

Conversely, sodium-rich dried abalone blood itself could be explored as a natural salt alternative, representing a potential niche application. Protein fractions, dominated by hemocyanin, which constitutes up to 90% of hemolymph protein, are of particular interest for their functional and bioactive properties. Importantly, preliminary elemental analysis detected only low levels or absence of heavy metals, and FSANZ (2025) has previously classified abalone blood as a non-traditional, non-novel food with no major safety concerns. This regulatory context suggests that, compared to viscera or shell, abalone blood may face fewer barriers to commercialisation as a food or ingredient.

6.4.2 Conclusion

The analysis of abalone blood confirmed its low dry matter content (~5%), dominated by ash and protein, with hemocyanin representing the major protein fraction. High sodium levels reflect the ionic balance with seawater and present both constraints and opportunities for utilisation. While elevated sodium may limit direct applications in food or pet products, sodium-rich dried blood could be explored as a natural salt alternative, and well-established separation techniques suggest great potential for hemocyanin

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recovery in a commercial scale. Importantly, low heavy metal levels and FSANZ's recognition of abalone blood as a non-traditional, non-novel food with no major safety concerns suggest a comparatively straightforward pathway to commercialisation.

6.4.3 Recommendations and Next Steps

- Trial separation methods (e.g., centrifugation, filtration) to isolate hemocyanin and reduce sodium content for broader applications.
- Conduct functional testing of hemocyanin for antioxidant, immunological, and bioactive properties relevant to nutraceutical and cosmeceutical markets.
- Potentially explore sodium-rich dried abalone blood as a natural salt substitute.
- Collect mineral and protein composition across seasons and species to identify key factors driving variability that may influence commercial processing.
- Undertake early-stage consultation with industry partners to test the technical feasibility of processing abalone blood at a commercial scale.
- Present safety and compositional data to FSANZ if abalone blood is to be developed as a food ingredient or product.

7. Assessment of Valorisation Pathways

7.1 Functional Assessment

Based on preliminary analysis results, literature reviews, and stakeholder consultations, subsequent experiments were conducted to evaluate the unique functionalities of transformed abalone waste streams under targeted valorisation options. These assessments focused on pathways most closely aligned with the principles of SDG 12.3, while also considering feasibility, stakeholder acceptance, and the creation of sustainable value.

7.1.1 Viscera

Crude usage of abalone viscera was proposed as a near-term valorisation pathway, positioned as a functional pet food ingredient and marketed as a sustainable alternative to freeze-dried, Green-Lipped Mussel (GLM; *Perna canaliculus*). This approach offers high feasibility, strong stakeholder acceptance, and alignment with existing "functional whole food" strategies, while enabling utilisation of more than 50% of the waste stream. In parallel, enzymatic hydrolysis was identified as a longer-term strategy, particularly suited for higher-value applications with partners such as Procter & Gamble (P&G) in cosmeceuticals. Hydrolysates not only enhance bioactivity but, when produced in liquid form, also provide opportunities for heavy metal reduction, supporting both safety and sustainability goals. Details could be found in Chung (2025) and Chung et al. (2025b).

7.1.1.1 Method – Freeze-dried Abalone Viscera

Functional properties of crude, freeze-dried abalone viscera were assessed using the same 11 samples analysed in preliminary studies. Nutritional quality was evaluated through established indices, including Total Antioxidant Amino Acids (AAA), Essential Amino Acid Index (EAAI), Predicted Protein Efficiency Ratio (p-PER), Predicted Biological Value (p-BV), Index of Atherogenicity (IA), Index of Thrombogenicity (IT), Hypocholesterolemic/Hypercholesterolemic Ratio (HH), and Health-Promoting Index (HPI), calculated from amino acid and fatty acid profiles (Chung et al., 2024a).

Antioxidant activity was investigated via a 4×2 factorial solid–liquid extraction design to compare abalone viscera with GLM. Four solvents (80% acetone, 80% methanol, 80% ethanol, and deionised water) and two extraction conditions (cold extraction: 4°C for

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24h; thermal extraction: 60°C for 20min) were applied, with screening conducted using the ABTS radical scavenging assay as described in Chung (2025) and Chung et al. (2025b).

In addition, total N-sulfated, and O-sulfated glycosaminoglycans (sGAGs) were quantified in both abalone viscera and GLM for comparative purposes as described in Chung (2025) and Chung et al. (2025b).

7.1.1.2 Results & Discussion – Freeze-dried Abalone Viscera

The nutritional indices of abalone viscera across the four commercially harvested wild species (Greenlip, Blacklip, Brownlip, and Roe's) demonstrated consistently high protein quality and valuable fat-related health attributes. The EAAI ranged from 81–85, reflecting a well-balanced amino acid profile suitable for human nutrition, while the p-BV of 77–81 indicates efficient utilisation of visceral proteins in the human body. These values are comparable to other high-quality protein such as casein and beef, and considerably higher than those reported for abalone muscle (~60), underscoring the superior nutritional value of viscera proteins. Similarly, the p-PER was 2.44–2.48, aligning closely with casein (≈2.5), further confirming viscera proteins as a high-quality dietary source. AAA content was stable across species (~49mg/100g protein), comparable to values obtained from Pacific Abalone, supporting viscera as a strong candidate for antioxidant-linked functionalities.

In terms of lipid-derived nutritional indices, abalone viscera showed a favourable profile for human health. IA and IT were consistently low (IA: ~0.54–0.60; IT: ~0.28–0.32), suggesting a reduced risk of cardiovascular disease compared with many terrestrial animal fats when consumed as a food source. HH was comparably high (2.2–2.5), while HPI ranged between 3.3–3.7, reflecting a predominance of beneficial fatty acids in line with those found in other marine oils. Collectively, these indices highlight abalone viscera lipids as a promising source of heart-healthy fatty acids, complementing their strong protein quality.

The intrinsic bioactivity evaluation further confirmed the potential of abalone viscera when benchmarked against GLM, a well-established marine nutraceutical. In terms of sGAGs, abalone viscera demonstrated a striking advantage, with concentrations ranging from 7.10–75.55mg/g, dry basis, compared to only 1.66mg/g dry basis in GLM. These compounds are of major interest due to their regenerative, anticoagulant, anti-viral, anti-cancer, and anti-inflammatory properties (Chen et al., 2011, Valcarcel et al., 2017). Both GLM and abalone viscera were dominated by O-sulfated forms of sGAGs, linked to anti-coagulant, anti-allergic, and anti-inflammatory functions (Anower-E-Khuda et al., 2013, Griffin et al., 2014). This compositional advantage highlights abalone viscera as a competitive, and potentially superior, and more sustainable alternative to GLM for nutraceutical markets targeting joint health, anti-inflammatory effects, and skin health.

Antioxidant activity assays reinforced this advantage. Using a 4×2 (solvents×temperature) factorial design, GLM achieved its highest antioxidant activity in hot methanol extracts (0.96mg Trolox equivalents (TE)/g, dry basis), whereas abalone viscera consistently outperformed GLM, with values ranging from 1.11–2.55mg TE/g, particularly when extracted with hot or cold water. This finding is especially noteworthy as it demonstrates that abalone viscera antioxidants are water-soluble, heat-stable, and extractable with inexpensive, environmentally friendly, and non-toxic solvents. This stands in contrast with GLM, which requires organic solvents for effective extraction, limiting its direct applicability in food-related contexts. The observation that even the lowest antioxidant value among abalone viscera samples exceeded GLM's maximum further underscores its superior antioxidant potential.

Together, these results suggest that abalone viscera not only matches but also potentially surpasses GLM in key nutritional and bioactive categories. The high protein quality, favourable lipid indices, enriched sGAG content, and strong antioxidant activity collectively support abalone viscera as a versatile functional ingredient with diverse applications. Potential pathways include pet food supplementation, nutraceutical and functional food products, and cosmeceuticals, all of which align with stakeholder priorities and the principles of SDG 12.3 by enabling utilisation of over 50% of this waste stream. Importantly, preliminary evidence that

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hydrolysis at 60°C does not degrade antioxidant activity supports compatibility with industrial-scale processing, while offering opportunities to further enhance bioactivity through enzymatic optimisation.

Details of these findings and further in-depth analyses are reported in Chung (2025), Chung et al. (2025b) and associated technical reports.

7.1.1.3 Conclusion – Freeze-dried Abalone Viscera

The nutritional and bioactive analyses confirm that abalone viscera are a high quality protein- and PUFA-rich waste, characterised by superior amino acid quality, favourable fat-related health indices, and markedly higher sGAG and antioxidant levels than GLM. These attributes position abalone viscera as a promising candidate for human and animal functional food/nutraceutical applications with minimal processing, while simultaneously advancing SDG 12.3 through high-yield and sustainable utilisation of this underused resource.

7.1.1.4 Method – Hydrolysed Abalone Viscera

Building on the literature review (Chung et al., 2025a) and enzyme screening studies, alcalase was identified as optimal for maximising material utilisation, while papain was selected for enhancing bioactivity. The initial design proposed sequential hydrolysis with both enzymes to combine yield and functionality. However, enzyme shortages between 2023 and 2025, linked to COVID-19 supply chain disruptions, limited access to both. As a result, the first trial applied papain hydrolysis across all 11 viscera samples, while subsequent work substituted alcalase in the most bioactive sample to progress the experimental program. Full methodological details of papain hydrolysis are provided in Chung et al. (2025b) and alcalase hydrolysis can be found in a separate publication draft (*Alcalase Hydrolysate in HaCaT Cells*).

Papain hydrolysates were analysed for total, N-sulfated, and O-sulfated sGAG using established protocols. Antioxidant potential was assessed through ABTS radical scavenging, DPPH radical scavenging, Ferric Reducing Antioxidant Power (FRAP), and Oxygen Radical Absorbance Capacity (ORAC), while anti-inflammatory potential was evaluated by enzyme inhibition assays targeting Cyclooxygenase-1 (COX-1), Cyclooxygenase-2 (COX-2), 5-Lipoxygenase (5-LOX), and 15-Lipoxygenase (15-LOX), with results presented as IC_{50}, potency, and selective index (SI) (Chung et al., 2025b).

Following *in vitro* analyses, HaCaT skin cell model was utilised to evaluate the hydrolysate's potential application as a dermatological antioxidant. Cytotoxicity was first assessed using Calcein AM (CAM) immunofluorescence assays and CM30 live-cell monitoring. Hydrolysates at varying concentrations were then applied to H_2O_2-stressed HaCaT cells to evaluate oxidative stress rescue capacity, quantified by WST-1 viability assays and supported by morphological observations under fluorescent widefield microscopy. This work has now ceased due to the project ending, but further details, underpinning next steps, are provided in a separate technical report – *Abalone Hydrolysate in HaCaT cell model*.

7.1.1.5 Results & Discussion – Hydrolysed Abalone Viscera

The compositional and functional analyses establish abalone viscera as a unique, high-value bioactive resource. sGAG content was remarkably high (11.69–75.54mg/g, dry basis), exceeding levels in other marine invertebrates (~5mg/g) (Kozlowski et al., 2011) and even surpassing conventional terrestrial sources such as porcine intestinal mucosa (0.22mg/g) (Linhardt et al., 1992). These findings align with earlier reports on Australian Blacklip Abalone viscera (8.24mg/g; Suleria et al., 2017) after moisture normalisation (Chung et al., 2024). This enrichment is likely linked to abalone physiology as an osmoconformer, maintaining isotonic balance with seawater, resulting in charged biomolecule accumulation within extracellular matrices (Gao et al., 2017, Yamada et al., 2011). High crude mineral levels (Na^+, K^+, Mg^{2+}, PO_4^{3-}) reported in viscera in preliminary analyses further support a biochemical environment conducive to polysaccharide sulfation (Chung et al., 2024c). Moreover, the defensive role of sGAGs in

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pathogen resistance may explain their concentration in visceral tissues, which are directly exposed to the external marine environment (Hooper et al., 2007, Yamada et al., 2011).

Analysis of sulfation patterns revealed that all samples were dominated by O-sGAGs (≥81%), consistent with other marine invertebrates such as sea cucumbers and sea urchins (Hossain et al., 2023, Vilela-Silva et al., 2008). The presence of galactose- and fucose-rich monomers suggests chemical similarity to fucoidan, a well-documented O-sulfated polysaccharide with strong antioxidant and anti-inflammatory properties (Fonseca and Mourão, 2021, Ghelani et al., 2022). While further structural validation is required, these findings suggest that abalone viscera could offer fucoidan-like functionality with higher yields and lower production costs compared to existing marine sources.

Hydrolysates derived from abalone viscera also demonstrated significant anti-inflammatory potential. Inhibition of COX-1 and COX-2 enzymes was observed across all samples, with IC_{50} values of 0.39–2.31mg/mL (COX-1) and 0.78–15.88mg/mL (COX-2). In several cases, COX-1 inhibition potency was comparable to that of natural marine-derived compounds (Francis and Chakraborty, 2020a, b, Makkar and Chakraborty, 2018, 2017). SI predominantly classified hydrolysates as non-selective COX inhibitors (SI 0.5–3.0), a profile considered advantageous in avoiding adverse side effects of highly selective inhibitors (Patrignani, 2000, Suleyman et al., 2007). Importantly, hydrolysates also inhibited 5-LOX and 15-LOX (IC_{50}: 1.66–5.44mg/mL), which are alternative inflammatory pathways that could be increased from COXs inhibition, broadening their anti-inflammatory spectrum and reducing risks of side effects commonly found in NSAIDs resulting from arachidonic acid shunting. These balanced inhibitory activities suggest that abalone viscera hydrolysates may function as wide-spectrum modulators of inflammation, offering safer alternatives to conventional NSAIDs, which have market demand (Fiorucci et al., 2001, Low et al., 2024).

During COXs inhibition, oxygen radicals could form, attenuating the underlying drivers of inflammation and reduce effectiveness of systemic anti-inflammatory interventions. Thus, to explore whether hydrolysates provide additional advantages in remediating underlying oxidative stress, antioxidant assays were evaluated (Fiorucci et al., 2001). Results further reinforced the functional potential of visceral hydrolysates. Among the four assays employed, ABTS exhibited the highest activity (136–285mg TE/g), followed by ORAC (70–124mg TE/g), DPPH (21–57mg TE/g), and FRAP (3–5mg TE/g). Stronger performance in ABTS and ORAC, both aqueous-based assays, indicates that abalone hydrolysate antioxidants are predominantly water-soluble, fast-acting, and stable at neutral pH. This contrasts with terrestrial protein hydrolysates, which often require organic solvents for comparable extraction (Zhu et al., 2023). Mechanistically, results suggest a preference for single electron transfer (SET) processes, consistent with earlier reports of antioxidant peptides isolated from abalone viscera (Liu et al., 2023).

Taken together, these findings establish abalone viscera as an abundant and sustainable source of highly bioactive compounds. Elevated sGAG content, dominated by O-sulfated forms, confers opportunities for applications in joint health, skincare, and anti-inflammatory nutraceuticals. Hydrolysates not only exhibit potent antioxidant activity but also balanced inhibition of COX and LOX pathways, highlighting their potential as broad-spectrum modulators of oxidative stress and inflammation. This aligns strongly with the need for safer, natural alternatives to synthetic anti-inflammatories and underpins the commercial promise of abalone viscera valorisation.

The alcalase-derived abalone viscera hydrolysates displayed dose-dependent effects on HaCaT cell viability. CAM fluorescence and CM30 live monitoring confirmed that concentrations ≤2µg/mL were generally biocompatible, maintaining confluence and metabolic activity similar to untreated controls. At ≥4µg/mL, however, viability declined sharply, reaching LD_{50} thresholds, and was almost completely abolished at 8µg/mL. This defined 2µg/mL as the practical safety limit for keratinocyte applications, which was lower than non-toxic dosages identified in previous HaCaT cell studies utilising abalone extract (50-200µg/mL) (Kim et al., 2024) and alcalase hydrolysate (12.5–50µg/mL) (Kang et al., 2024).

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Oxidative stress assays using H_2O_2 (LD_{50} ~1mM) demonstrated that abalone viscera hydrolysates failed to rescue cells from oxidative damage at either 30min or 24h pre-incubation. In contrast to the positive control (AA2P), which enhanced survival in a dose-dependent manner, abalone viscera hydrolysates consistently yielded survival rates equal to or below H_2O_2 controls. Microscopy reinforced these findings: cells at ≤2µg/mL retained confluent morphology, whereas higher concentrations caused detachment, reduced CAM fluorescence, and extensive cell death, particularly in oxidative stress conditions.

The absence of protective antioxidant effects in the HaCaT model, despite strong activity in chemical assays, may be explained by stability challenges inherent to abalone viscera hydrolysates. Freeze-dried abalone viscera hydrolysates are highly hygroscopic due to their abundance of charged molecules, making them prone to moisture absorption during storage, even at −80°C. This could have led to peptide degradation, Maillard reactions, and hydrolysis of sulfated polysaccharides, resulting in diminished bioactivity (Rao et al., 2016, Cassani et al., 2020). Such instability reflects a broader challenge noted in the commercialisation of marine protein hydrolysates, where hygroscopicity and short shelf-life are major hurdles (Mohan et al., 2015, Shahidi and Saeid, 2025, Pavlicevic et al., 2020). Stabilisation strategies such as spray-drying with binders, encapsulation, or co-formulation may therefore be essential to preserve functionality over time.

In addition, the observed cytotoxicity at higher concentrations may be linked to increased heavy metal bioavailability after hydrolysis, a hypothesis identified during the literature review (Chung et al., 2025a) and observed in Qi et al. (2020). Importantly, this does not preclude hydrolysates as a viable pathway, since heavy metals can be more effectively removed during liquid-stage processing, especially in abalone viscera hydrolysate, as suggested by Xu et al. (2017) and Weng et al. (2019).

Despite these limitations, the broader body of evidence supports abalone viscera hydrolysates as strong candidates for skin-related applications. With the incorporation of stabilisation strategies (e.g. spray-drying with binders, encapsulation, or co-formulation) and liquid-stage heavy metal removal, the high intrinsic bioactivity of AV hydrolysates can be preserved and translated into practical products. Their alignment with cosmeceutical and nutraceutical market demands (e.g. P&G) provides a compelling rationale for continued development and industrial scaling. Full details on the assessment of AV hydrolysates for skin-related cosmeceutical applications, including cell study outcomes, are presented in separate technical reports.

7.1.1.6 Conclusion – Hydrolysed Abalone Viscera

Abalone viscera hydrolysates exhibit high intrinsic bioactivity, characterised by elevated sulfated glycosaminoglycans, strong antioxidant potential, and broad-spectrum anti-inflammatory activities through inhibition of COX and LOX pathways. Despite challenges in stability and cytotoxicity observed in the HaCaT cell model, likely linked to the hygroscopic nature of freeze-dried hydrolysates and potential heavy metal bioavailability, these limitations can be addressed through stabilisation strategies and integrated metal-removal steps. Overall, abalone viscera hydrolysates remain a promising pathway for long-term valorisation, with significant potential in nutraceutical and cosmeceutical applications, especially those targeting inflammation, oxidative stress, and skin health.

7.1.1.7 Conclusion – Viscera

Abalone viscera hydrolysates demonstrate high intrinsic bioactivity, with elevated sulfated glycosaminoglycans, potent antioxidant capacity, and balanced anti-inflammatory effects via COX and LOX inhibition. While stability issues and cytotoxicity in the HaCaT model suggest challenges linked to the hygroscopic nature of freeze-dried hydrolysates and potential heavy metal bioavailability, these can be mitigated through stabilisation technologies and liquid-phase metal removal. Importantly, crude usage data provide sufficient evidence that abalone viscera already deliver enhanced nutritional and bioactive functionalities compared to GLM, supporting their immediate use as a high-value alternative in pet food and functional food markets. Taken together, crude usage

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offers a strong near-term pathway, while hydrolysates provide a longer-term opportunity for nutraceutical and cosmeceutical development, particularly for inflammation, oxidative stress, and skin health applications.

7.1.1.8 Recommendations and Next Steps – Viscera

- Undertake targeted functional testing of viscera-derived products in joint health, skin health, and anti-inflammatory models using advanced cell culture and organoid systems, in alignment with P&G's no-animal-testing directive.
- Explore regulatory approval pathways under FSANZ and ACNF to determine the eligibility of both freeze-dried and hydrolysed viscera as novel functional food or nutraceutical ingredients.
- Benchmark consumer acceptance by comparing freeze-dried abalone viscera with existing GLM products, to support evidence-based market differentiation and product positioning.
- Initiate pilot-scale trials with ACA members and industry partners to refine processing workflows and evaluate technical and commercial scalability of both pathways.
- Assess the shelf-stability of hydrolysates (for which no data currently exist) and apply stabilisation strategies such as encapsulation if instability is confirmed.
- Investigate combined-enzyme hydrolysis (alcalase + papain) to optimise the yield and functionality of viscera hydrolysates.
- Evaluate heavy metal safety risks and implement mitigation strategies (e.g., citric acid chelation) to proposed processing, ensure compliance with food safety standards.

7.1.2 Shell

Based on preliminary analyses above, crude usage of abalone shell as a natural calcium supplement was identified as a near-term valorisation pathway, positioned as an alternative to conventional inorganic calcium supplements and comparable to other shell-derived supplements already marketed in the US, Netherlands, and Japan (Chang et al., 2007, Morris et al., 2019, Chung et al., 2024b). A key point of differentiation from oyster shell, which dominates the market, lies in abalone shell's traditional recognition as an oriental medicine under the name *shijueming* (石决明; 석결명; セッケツメイ) or *Concha Haliotidis*, across countries such as Japan, China, Korea, and the Philippines. Grey literature and historical usage provide evidence of additional human health benefits, offering a marketing advantage that complements its nutritional function (details provided in a separate technical report – *Medicinal Use of Abalone Shell*). This pathway offers high feasibility, strong stakeholder acceptance, and alignment with existing "functional whole food" strategies, while enabling near-total utilisation of shell waste with minimal processing. Moreover, consumer preference for natural, marine-derived calcium sources enhances the competitiveness of this approach in the health food and nutraceutical sectors.

In parallel, the development of purified aragonite using novel, regenerative, and scalable processing methods was identified as a longer-term strategy. This pathway is particularly suited to address critical supply gaps in biomedical industries, where aragonite is used in bone-regenerative medical products but is currently sourced from labour-intensive and low-yield processes requiring nacre from specific organisms (e.g., giant freshwater clams or pearl shells). The rapid growth of aragonite-based biomedical supplies (e.g., PearlBone™) has highlighted major scalability constraints due to sourcing limitations (Zheng, 2025). Abalone shells, with their abundant and underutilised supply, represent a promising alternative feedstock, offering both supply security and alignment with sustainable, circular economy principles.

Additionally, calcium carbonate has shown strong potential in sustainable packaging, where it enhances the strength, thermal stability, and barrier properties of biopolymers such as PLA and starch films, while also improving biodegradability and reducing oxygen and moisture permeability. Its low toxicity, cost advantage compared to pure biopolymers, and role in reducing food

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spoilage further support its integration into circular economy frameworks, positioning abalone shell-derived calcium carbonate as a multifunctional, eco-friendly material for next-generation packaging (Cai et al., 2025).

A full-length discussion on the rationale can be found in Chung et al. (2024b).

7.1.2.1 Method – Shell Characterisation

To characterise the physicochemical and structural properties of abalone shell for potential uses, a suite of analytical techniques was conducted, including Thermogravimetric Analysis (TGA), X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Fourier-Transform Infrared Spectroscopy (FTIR). TGA was performed on finely ground Roe's and Greenlip shell samples (10–20mg; harvested from Augusta, WA) from ambient to 800°C at 10°C/min under nitrogen to assess thermal stability and composition. XRD analysis was carried out on micronized samples (with 10wt.% corundum as internal standard) using a Bruker D8 Advance diffractometer with Cu Kα radiation (5–80° 2θrange) to identify crystalline phases via Rietveld refinement. SEM imaging was conducted on platinum-coated samples using a Zeiss Neon 40EsB microscope at 10 kV to observe microstructure and morphology, while FTIR spectra were collected (4000–450cm^{-1} range) using a Nicolet iS50 spectrometer in ATR mode to identify carbonate polymorphs through characteristic vibrational bands. Full methodological details are reported in Chung et al. (2024b).

7.1.2.2 Results & Discussion – Shell Characterisation

SEM imaging revealed a lamellar nacreous structure (~400–500nm thick) interspersed with columnar calcite, with particle sizes ranging from <1µm to 1mm. This morphology supports dual valorisation pathways, as a high-bioavailability supplement and as a functional filler in biocomposites, due to enhanced surface reactivity and tortuosity effects. XRD analysis identified aragonite as the dominant $CaCO_3$ polymorph (75–78%, w/w in abalone shells), with calcite (~10–18%) and minor amorphous content (<2%). The exceptionally high aragonite proportion, compared with other commercial shell sources (e.g., oyster, mussel), highlights abalone shell's superior suitability for biomedical and regenerative applications due to aragonite's bioactive and osteoconductive properties. FTIR spectra corroborated these findings, showing characteristic aragonite bands at 1083cm^{-1}, 713cm^{-1} and 700cm^{-1}.

TGA confirmed excellent thermal stability, with decomposition of $CaCO_3$ to CaO occurring above 650°C and only minor organic loss (<4%) below 240°C. This high stability underscores the potential use of abalone shell as a thermal stabiliser or filler in sustainable biopolymers such as PLA or starch-based films. Combined, these findings demonstrate that abalone shell represents a versatile, high-purity natural mineral resource with strong potential for nutraceutical, biomedical, and sustainable packaging applications, provided heavy metal safety and regulatory validations are addressed. Full-length analytical discussion is available in Chung et al. (2024b).

7.1.2.3 Conclusion – Shell Characterisation

The comprehensive physicochemical analyses confirm that abalone shell is a high-purity, structurally distinct biomaterial, rich in bioactive aragonite and possessing excellent thermal stability. These properties support its dual valorisation as a natural calcium supplement and as a functional filler in biopolymer packaging and biomedical materials. Compared to conventional shell sources, the superior aragonite content and lamellar microstructure of abalone shell provide a unique competitive advantage for applications requiring biocompatibility, structural reinforcement, or mineral bioavailability. With further validation of heavy metal safety and regulatory compliance, abalone shell represents a scalable, sustainable, and commercially attractive resource for circular economy product development across the health, packaging, and regenerative medicine sectors.

7.1.2.4 Method – Regenerative Aragonite Purification

Adapting purification principles commonly employed in the mineral processing sector, a regenerative and scalable method was developed to isolate aragonite from molluscan shell waste. While abalone shells are intrinsically high in aragonite, lower-aragonite

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content shell material, specifically Akoya Oyster (*Pinctada fucata*) shell (~40%), was selected for method optimisation to ensure suitability for mixed-species processing and to maximise separation efficiency.

Heavy liquid separation using sodium polytungstate (SPT) was applied to differentiate calcium carbonate polymorphs. An SPT solution with a target density of 2.8g/cm^3 was prepared by gradually dissolving SPT powder into deionised water (mass ratio 82:18) heated to 60°C under continuous magnetic stirring. After cooling to room temperature, the solution was adjusted to pH ~8 using sodium hydroxide (NaOH) to suppress calcium carbonate decomposition. For each separation cycle, 50g of ground shell powder was suspended in 200mL of the SPT solution and gently stirred to form a uniform suspension. The mixture was left undisturbed for 3–4hrs to allow for gravity-based separation. Less dense, calcite-rich particles were collected from the surface, while aragonite-enriched fractions settled at the bottom. The intermediate liquid layer was decanted, and the SPT solution was recovered via vacuum filtration, density-checked, and reused in a second cycle to improve phase purity. Separated solids were thoroughly rinsed with DI water to remove residual SPT, oven-dried at 110°C, and stored. To prevent calcium tungstate ($CaWO_4$) formation during storage, the recovered SPT solution was acidified to pH 2 using hydrochloric acid (HCl).

To confirm the effectiveness of the separation and identify mineralogical composition, the resulting fractions were analysed using SEM, FTIR and XRD. Full methodological details are available in a separate master's thesis (*aragonite separation*) supporting this report and available on request from the CRC or project authors.

7.1.2.5 Results & Discussion – Regenerative Aragonite Purification

The two-cycle heavy liquid separation protocol using SPT successfully demonstrated a regenerative, scalable method for isolating high-purity aragonite from molluscan shell powders, even when starting with shells that contain relatively low native aragonite levels. Quantitative XRD analysis confirmed a final aragonite purity of 97.6% in the heavy (bottom) fraction (**Error! Reference source not found.**), representing a significant enrichment from the untreated oyster shell baseline (~40% aragonite), which also included calcite, scheelite, and other minor phases. In contrast, the light (top) layer was predominantly calcite (84.5%) with minimal aragonite (12.1%), confirming successful density-driven phase separation. The clear visual stratification observed between the white and brown layers (Figure 1) further reinforced the effectiveness of this approach.

FTIR analysis supported these findings by identifying sharp aragonite-specific vibrational bands at ~1083, 856, and 700cm^{-1} in the purified bottom fraction. SEM imaging revealed distinct needle-like and radiating microstructures consistent with aragonite crystals, validating the structural integrity of the separated material. Importantly, the process demonstrated high repeatability over multiple cycles, with the SPT solution remaining reusable following basic pH correction, showing no significant loss in separation efficiency. Acidification of the recovered liquid to pH ~2 effectively prevented the formation of calcium tungstate ($CaWO_4$), enabling multiple reuse cycles and supporting the environmental sustainability of the method.

Taken together, these results confirm that heavy liquid separation using SPT offers a regenerative, low-waste, and high-precision route for aragonite isolation. This technique is particularly valuable for co-processing mixed shell species and buffering supply inconsistencies common with abalone-derived waste (Loo, 2023). With its high-purity output and compatibility with biomedical, nutraceutical, and advanced materials markets, this scalable method represents a viable circular economy solution for valorising marine shell waste, especially when applied to high-aragonite species like abalone. Full results and discussion are available in a separate master's thesis (*Aragonite Separation*) and data set (*Data – Aragonite Purity*).

7.1.2.6 Conclusion – Regenerative Aragonite Purification

The heavy liquid separation process developed for isolating aragonite from molluscan shells has demonstrated strong technical, economic, and environmental viability. The method achieved high-purity aragonite (up to 97.6%) from low aragonite feedstocks without the need for high labour, heat or energy input, setting it apart from conventional thermal or acid-based purification

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techniques. Its regenerative nature, enabled by the reusable SPT solution and minimal waste generation, further enhances its sustainability profile, aligning with circular economy and low-carbon manufacturing principles.

Given the intrinsic high aragonite content of abalone shells, this method is particularly well-suited to valorise existing waste streams, while also enabling co-processing of other molluscan shells with variable compositions. Coupled with rising global demand for aragonite in biomedical, nutraceutical, and sustainable materials sectors, this approach offers significant commercial potential as a low-cost, scalable solution for producing high-value aragonite from abalone waste and could potentially be adapted to other shellfish industries.

7.1.2.7 Method – Functional Packaging

Roe's Abalone shells were soaked, thermally charred, and finely ground to <45µm particle size. These were then blended with desiccated PLA at varying inclusion rates (0%, 15%, and 30%) to produce prototype biopolymer films via film-casting. The resulting films underwent comprehensive physical characterisation, including barrier property analysis (water vapour transmission rate) and mechanical performance testing, specifically, tensile strength, puncture resistance, perforation behaviour, and dynamic mechanical analysis, to identify the optimal shell inclusion level for packaging functionality.

Following these assessments, 15% shell-infused PLA films (identified as the optimal ratio) were selected for a simulated shelf-life trial using minced Atlantic Salmon (*Salmo salar*). Packaging performance was evaluated over 7 and 14days of refrigerated storage by monitoring key spoilage indicators: physical (colour), chemical (pH, total volatile basic nitrogen [TVB-N], thiobarbituric acid reactive substances [TBARS]), and microbiological (total viable count) parameters.

Full details of the formulation, testing protocol, and results are available in a separate publication draft (*Publication – Shell-Infused Packaging*) and thesis (*Abalone Shell PLA Packaging*).

7.1.2.8 Results & Discussion – Functional Packaging

Results are presented in a separate publication draft (*Shell-Infused Packaging*) and thesis (*Abalone Shell PLA Packaging*). Incorporation of 15% abalone shell powder into PLA films significantly influenced both mechanical and functional characteristics of the resulting bio-based packaging material. Mechanical testing revealed a clear trade-off with ASP-PLA films exhibiting reduced tensile strength and puncture resistance compared to neat PLA (tensile strength: 384.08 vs. 573.39g/cm²; puncture resistance: 166.80 vs. 266.30g), yet demonstrated significantly improved elongation at break (2.90% vs. 1.54%). This suggests that while structural rigidity decreased, material flexibility increased, an advantageous feature for applications requiring pliable yet durable packaging.

From a functional standpoint, shell inclusion improved several indicators of food preservation. In simulated cold-storage trials using vacuum-packed minced salmon, ASP-PLA packaging reduced the accumulation of TVB-N, indicating suppression of protein degradation and spoilage-related reactions. Although TVC did not differ significantly between treatments, a visible reduction in microbial proliferation was observed in fish mince stored within ASP-PLA films. This supports the potential role of shell inclusion in attenuating bacterial activity and endogenous proteolytic enzyme function, both key drivers of spoilage and food waste (Chung et al., 2021).

The observed shelf-life extension could be attributed to several interacting mechanisms: (1) improved barrier properties, as evidenced by reduced water vapour transmission; (2) intrinsic pH-buffering effects of calcium carbonate (Basdeki et al., 2024); (3) possible antimicrobial activity associated with calcium oxide (CaO) traces (Kim et al., 2007); and (4) enhanced reactive surface interactions from nano-sized calcium carbonate particles (Kamel et al., 2021) within the shell matrix.

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However, ASP-PLA films also exhibited certain undesirable quality changes, including increased lightness, elevated TBARS, and reduced chroma, all indicative of lipid oxidation processes in *Salmo salar* (Chung et al., 2024a). These outcomes may stem from incomplete demineralisation during shell preparation, which could elevate pro-oxidative trace metals and catalyse Fenton-type lipid peroxidation reactions (Hasan et al., 2019, Benedet and Shibamoto, 2008, Repetto et al., 2010). Thus, refinement of the demineralisation protocol is warranted to minimise oxidation and improve product stability.

Despite these limitations, the prototype demonstrates encouraging functionality. The combined benefits of enhanced insulation (Basdeki et al., 2024), biodegradability, and material cost reduction (Basdeki et al., 2024) strengthen the case for ASP as a multifunctional filler in biopolymer packaging. Future optimisation could involve additional particle size reduction (Kamel et al., 2021), conversion of intrinsic $CaCO_3$ to CaO (Lu et al., 2022, Chung et al., 2024b), or modification of $CaCO_3$ through compositing with functional bioactives (Rüegg et al., 2022), all strategies that have shown proven effectiveness in enhancing shelf-life and performance in prior studies.

7.1.2.9 Conclusion – Functional Packaging

The incorporation of abalone shell powder into PLA matrices demonstrated a promising valorisation pathway for abalone shell waste, combining functional performance enhancement with strong alignment to sustainability and circular economy principles. Despite a reduction in mechanical rigidity, the developed ASP-PLA films exhibited improved flexibility, enhanced moisture barrier properties, and measurable benefits in preserving food quality through reduced protein degradation and spoilage indicators. These outcomes confirm the technical feasibility of using shell-derived calcium carbonate as a multifunctional filler that contributes to both material performance and food preservation.

While further optimisation is required, particularly in refining demineralisation to mitigate lipid oxidation and improve oxidative stability, the current findings validate the potential of abalone shell–infused biopolymers as a viable alternative to conventional petroleum-based packaging. The system's biodegradability, cost-effectiveness, and capacity to utilise an existing marine waste strengthen its commercial relevance and environmental credentials. With additional process refinement and scale-up, ASP-PLA packaging could serve as a solution that supports reduced food waste, promotes sustainable materials innovation, and advances Australia's blue bioeconomy.

7.1.2.10 Recommendations and Next Steps – Shell

- Explore approval under FSANZ and ACNF frameworks for the classification of abalone shell as a novel functional food ingredient, natural calcium fortification agent, or nutraceutical component, ensuring compliance with food safety and quality standards.
- Conduct targeted consumer acceptance studies comparing abalone shell–derived calcium supplements and fortified food products (e.g., dairy) against existing commercial alternatives to establish market differentiation and trust in "marine-sourced calcium" branding.
- Initiate pilot-scale production with ACA members and partnering processors to optimise workflow, assess scalability, and validate economic feasibility across different product pathways, including supplements, functional fillers, and packaging additives.
- Assess potential for IP protection related to the newly developed regenerative and low-energy aragonite purification technology, positioning it as a proprietary, environmentally friendly process with commercial licensing potential
- Discuss direction of advancing research of valorisation pathways (i.e. as purified aragonite, functional filler, or potentially convert shell to CaO for sustainable self-heating packaging.

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7.1.3 Blood

Previous research and anecdotal evidence have indicated that abalone blood may possess strong antiviral potential, particularly against herpes simplex virus type 1 (HSV-1), due to its close genetic resemblance (~80%) to abalone herpesvirus (AVG) (Jiada et al., 2018). The same study proposed that some Australian abalone species may have evolved natural immunity and antiviral resistance as a result of selective survival during historical AVG outbreaks, suggesting that their haemolymph may contain bioactive compounds with therapeutic potential.

Among these, hemocyanin, a copper-based oxygen carrier unique to molluscs, has been identified as a key bioactive molecule with potential for value-added applications. Previous studies have demonstrated that abalone hemocyanin exhibits antiviral and immunostimulatory activities and can be processed into a shelf-stable therapeutic ingredient (Zanjani et al., 2014). However, the broader spectrum of bioactivities associated with abalone blood, such as antioxidant or anti-microbial functions, remains largely unexplored. Furthermore, most existing studies rely on blood collected under sterile, laboratory-controlled conditions, with limited evidence on the feasibility of using blood derived from abalone processing, a waste typically discarded during commercial harvesting.

Importantly, while previous work has focused primarily on purified hemocyanin, whole abalone blood, comprising haemolymph and its associated bioactive molecules, may possess additional functional components. Evidence from other marine invertebrates, such as the Horseshoe Crab (*Limulus polyphemus*), has shown that haemolymph contains a wide array of biologically active substances that play central roles in innate immunity and oxidative stress regulation (Armstrong and Conrad, 2008). This suggests that abalone haemolymph may similarly harbour diverse bioactive constituents beyond hemocyanin, potentially contributing to its nutritional and therapeutic value.

To explore this hypothesis, the present investigation focused on characterising the intrinsic bioactive potential of abalone blood, with emphasis on antioxidant and antimicrobial functions, as a foundation for future functional and nutraceutical development. Additionally, processing interventions such as shelf-stability treatments (Zanjani et al., 2014) and enzymatic hydrolysis, previously shown to enhance bioactivity in abalone viscera, were explored to evaluate their potential to preserve or improve functionality.

This two-tiered approach, examining both raw and value-added forms, aims to determine whether abalone blood, as a readily available processing waste, can be upcycled into a high-value biofunctional ingredient. Such valorisation aligns strongly with circular economy principles and SDG 12.3, promoting the sustainable utilisation of marine resources while unlocking new opportunities in nutraceutical, cosmetic, and functional food applications.

7.1.3.1 Method

Methods for the investigation of antimicrobial and intrinsic antioxidant activities of abalone blood obtained from Greenlip, Blacklip and Roe's abalone (Augusta, WA) are detailed in the accompanying Master's thesis (*Abalone Blood*) and technical report (*Abalone Blood*). Antioxidant properties were assessed through multiple complementary assays, including total phenolic content (TPC), DPPH, ABTS and FRAP, to capture both hydrogen atom transfer (HAT) and single electron transfer (SET) mechanisms.

To evaluate antimicrobial potential, disc diffusion assays were conducted against three common foodborne pathogens: *Staphylococcus aureus*, *Escherichia coli*, and *Bacillus subtilis*. Preliminary testing was performed using crude abalone blood extracts derived from commercial processing waste streams.

Initial results indicated generally low bioactivities across both antioxidant and antimicrobial assays, supporting the hypothesis that conventional abalone blood extraction methods may lead to partial denaturation or degradation of active compounds. This loss of

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functionality is hypothesised to be linked to lipopolysaccharide (LPS) sensitivity and protein instability under standard handling conditions, similar to that observed in *Limulus polyphemus* (Horseshoe Crab) blood.

To address these limitations, a new stabilisation protocol was developed, adapting methodologies previously applied to Horseshoe Crab haemolymph stabilisation (Armstrong and Conrad, 2008). A 2×2 factorial treatment design was implemented to test the effects of stabiliser incorporation and post-extraction processing on bioactivity retention and enhancement. The optimised method aims to preserve native haemolymph functionality and improve compatibility with scalable, food-grade commercial processing.

While optimisation is ongoing, preliminary antimicrobial evaluations using minced pork as a food model have been conducted to assess potential food preservation applications. Future analyses (Phase 2) will include redox potential measurements and anti-HSV-2 activity assays to further validate antiviral and functional potential of the stabilised abalone blood fractions. Full methodological details and experimental data are available in the accompanying publication draft *"Functionality of Abalone Blood."*

7.1.3.2 Results & Discussion

Initial evaluation of abalone blood collected as a waste during commercial processing revealed low intrinsic antioxidant and antimicrobial activity, supporting the hypothesis that bioactive components such as hemocyanin and associated immune molecules may be unstable or degraded under non-sterile handling and post-harvest conditions. Antioxidant assays (TPC, DPPH, ABTS, FRAP) showed minimal activity across all parameters, consistent with the potential oxidation or denaturation of redox-active compounds during collection and storage. Similarly, antimicrobial testing against *S. aureus*, *E. coli*, and *B. subtilis* exhibited negligible inhibition zones, indicating a lack of measurable bacteriostatic or bactericidal effects in untreated, waste-derived blood. Full results and discussion in the Master's thesis (*Abalone Blood*) and technical report (*Abalone Blood*).

However, freshly collected blood subjected to preservation or enzymatic hydrolysis treatments within 48hrs demonstrated promising antimicrobial potential. Both treatments individually produced observable inhibition against pork's microflora, accompanied by observable reductions in colony density and growth rate relative to control samples. These results indicate that stabilisation and mild hydrolysis can enhance the exposure or bioavailability of antimicrobial constituents**,** likely including metal-bound proteins such as hemocyanin and associated peptide fragments.

Interestingly, when preservation and hydrolysis treatments were combined**,** the antimicrobial effect was nullified, suggesting possible interference rather than complete loss of bioactivity. One plausible explanation is a redox imbalance introduced by treatment interactions. Hydrolysis may have exposed Cu^{2+} ions from hemocyanin, which are known to exert antimicrobial effects via oxidative mechanisms (Yu et al., 2023). However, concurrent stabiliser treatment could have altered redox potential, potentially through the generation of antioxidant peptides, similar to those observed in viscera hydrolysates, thereby neutralising these effects.

Taken together, these findings indicate that abalone whole blood retains functional potential but is highly sensitive to post-harvest handling and processing sequence. The results suggest that, in a processed and properly stabilised form, abalone blood could exhibit significant bioactivity. Optimising collection, stabilisation, and hydrolysis protocols will therefore be critical to its commercial and functional potential as a marine-derived bioactive ingredient. Details of preliminary data are in *Data – Preliminary Anti-Microbial Activity of Abalone Blood.*

7.1.3.3 Conclusion

The findings indicate that while abalone blood collected as a processing waste exhibits low inherent antioxidant and antimicrobial activity, its biofunctional potential can be substantially enhanced through appropriate post-harvest treatments. Freshly collected blood treated with either preservation or enzymatic hydrolysis within 48 hours demonstrated clear antimicrobial effects, suggesting that active constituents such as hemocyanin-derived peptides and copper-associated complexes retain functionality under

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appropriate handling. However, the nullification of bioactivity when both treatments were combined highlights the importance of investigating underlying mechanisms, such as alteration to redox potential.

Importantly, the regulatory framework governing abalone blood offers a significant advantage for commercialisation. FSANZ has previously classified abalone blood as a non-traditional, non-novel food (FSANZ, 2025), meaning that its use as a human food ingredient does not face the same level of regulatory barriers as other waste streams. This provides a streamlined pathway for product development and market entry once stability and functional optimisation are achieved.

These results collectively suggest that abalone whole blood represents a promising, low-barrier, underutilised bioresource that can be transformed into a functional marine ingredient if appropriate stabilisation, concentration, and management strategies are developed. Its potential aligns with growing global demand for natural antimicrobial and antioxidant agents derived from sustainable sources. Future optimisation should therefore focus on refining lyophilisation and hydrolysis conditions, validating bioactivity at higher concentrations, and ensuring process scalability for integration into nutraceutical or biotherapeutic applications.

7.1.3.4 Recommendations and Next Steps

- Optimise stabilisation and commercially applicable processing protocols to preserve bioactivities of whole blood.
- Validate antimicrobial, anti-viral and antioxidant activities of lyophilised and concentrated blood fractions at higher dosages using both chemical and biological assays, including pathogen and cell-based models.
- Investigate shelf-stabilities of proposed post-harvesting methods and formulations to ensure translatability.
- Leverage FSANZ's classification of abalone blood as a non-traditional, non-novel food to expedite regulatory approval and market introduction compared to other waste streams.
- Explore integrated valorisation models that co-process abalone blood alongside viscera hydrolysates to maximise resource efficiency and align with SDG 12.3 sustainability objectives.

7.2 Safety Mitigation – Heavy Metal Reduction

To further strengthen the safety profile and market readiness of abalone viscera, a series of practical and translatable mitigation protocols were evaluated, prioritising simplicity and alignment with regulatory standards. These measures focused on reducing heavy metal content through affinity chelation and controlled thermal treatments, alongside ensuring compliance with FSANZ and international safety thresholds for functional and nutraceutical applications (Chung et al., 2024c). By integrating these interventions, abalone viscera can be positioned as a novel, safe, and ethically upcycled ingredient, supporting both consumer trust and commercial scalability in global markets.

7.2.1 Method

A 2×3 factorial intervention experiment was conducted to evaluate the effectiveness of different remediation strategies for reducing heavy metal content in lyophilised abalone viscera, identified as the most contaminated sample based on its HI. The first factor tested two thermal-time diffusion treatments: a high-temperature short-time (HTST) process (100°C for 15min) and a low-temperature long-time (LTLT) process (30°C for 30h), both previously reported to enhance metal diffusion in seafood and grains. The second factor assessed three extraction media, ultrapure water, 0.15M citric acid, and 0.15M sodium acetate, to compare the performance of simple diffusion versus organic acid and salt-based chelation. All treatments were conducted at a 1:10 (w/w) solid-to-liquid ratio under temperature-controlled conditions, and resulting samples were freeze-dried and analysed for elemental composition using MP-AES, ICP-MS, and CV-AFS. Subsequent HI and EDUL calculations quantified residual risk, enabling comparative assessment of the treatments and their combinations to identify the most effective and practical mitigation approach for heavy metal reduction in abalone viscera. Detail in Chung et al. (2024c).

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Based on the preliminary findings, an on-site validation trial was later conducted at a commercial abalone processing facility in Port Lincoln, South Australia, in collaboration with the South Australian Research and Development Institute (SARDI), using the optimised protocol from Chung et al. (2024c). Full details of this validation study are available in the accompanying technical report (*On-Site Validation of Heavy Metal Reduction*).

7.2.2 Results & Discussion

The on-site validation trial conducted at Port Lincoln confirmed the practical feasibility of simple remediation treatments for heavy metal reduction in abalone viscera under commercial processing conditions. Boiling in 0.15M citric acid produced promising results, particularly for iAs, which decreased by approximately 50% in intact fresh samples. Despite this substantial reduction, iAs concentrations remained above FSANZ safety thresholds for molluscan products (iAs >1mg/kg, wet basis), indicating that while citric acid chelation effectively enhances metal solubilisation, the current treatment parameters (15min, 0.15M) are insufficient for full compliance across Australia, particularly given that samples were randomly collected from a potentially high-iAs population.

These findings confirm that citric acid treatment represents a viable, low-cost, and food-safe approach for heavy metal mitigation in abalone viscera, consistent with food additive regulations and sustainability objectives. However, optimisation is required to further enhance the bioaccessibility and diffusion of bound metals, potentially through longer exposure times, higher acid concentrations, or multiple extraction cycles. Importantly, the current outcomes provide a strong foundation for developing HACCP-based safety control protocols, with critical limits now able to be defined for future industrial implementation. This approach may also inform corrective actions for high-metal samples within broader seafood processing operations.

Overall, the trial demonstrates encouraging progress toward establishing a scalable, industry-compatible decontamination process, offering a practical step toward improving the safety and market readiness of abalone viscera-derived products. Future work should explore pre-soaking, ultrasound-assisted diffusion, and multi-chelating systems to achieve greater reductions in heavy metal concentrations and full regulatory compliance. Further details are provided in the accompanying technical report (*On-Site Validation of Heavy Metal Reduction*).

7.2.3 Conclusion

The on-site validation confirmed that citric acid treatment is a promising, safe and cost-effective mitigation approach for reducing heavy metal content in abalone viscera, achieving close to 50% reduction in iAs under commercial processing conditions. Although current treatment parameters did not achieve full compliance with FSANZ limits, the demonstrated reduction provides a critical foundation for developing industry-scale HACCP protocols and establishing corrective actions for metal contamination control. The method's simplicity, compatibility with existing infrastructure, and reliance on food-grade reagents make it highly translatable to commercial applications. With further optimisation, such as extended diffusion times, multiple extraction cycles, or enhanced chelation, this process has the potential to fully meet safety standards, enabling the safe utilisation and market entry of abalone viscera-derived products.

7.2.4 Recommendations and Next Steps

- Investigate the impact of adjusting citric acid remediation parameters (e.g., longer soaking durations, higher acid concentrations, multiple treatment cycles) on heavy metal content to achieve full compliance with FSANZ heavy metal limits, particularly for inorganic arsenic (iAs).
- Conduct controlled pilot-scale trials across multiple abalone processing facilities to validate reproducibility and operational feasibility of the optimised treatment under industry conditions.

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- Integrate validated protocols into HACCP frameworks, establishing critical limits, monitoring procedures, and corrective actions for heavy metal contamination control in abalone viscera processing.
- Investigate advanced, synergistic remediation methods, such as combined organic acid–salt systems, or enzymatic pre-treatment to improve chelation efficiency and metal mobility.
- Evaluate nutrient retention and sensory quality post-treatment to ensure that mitigation processes maintain product integrity and consumer acceptability.
- Engage regulatory and industry partners (e.g., FSANZ, ACA, SARDI) to facilitate approval and adoption of the finalised protocol as a model for sustainable, safe valorisation of marine waste.

7.3 Summary of Recommendations and Next Steps

7.3.1 Viscera

Next steps for viscera valorisation should prioritise the commercialisation of low-barrier, high-feasibility pathways, particularly the development of crude freeze-dried viscera as a functional pet food ingredient. This pathway offers immediate commercial potential, supported by strong stakeholder acceptance, reduced regulatory barriers, and direct comparability to established GLM products. In parallel, efforts should continue to advance higher-value hydrolysate applications, with a focus on improving stability, shelf-life, and scalability through techniques such as encapsulation, spray-drying, or co-formulation. Collaboration with P&G should be maintained to align ongoing research with cosmeceutical development interests, as detailed in the accompanying technical report (*P&G Phase 0 Entry Assessment*). Notably, emerging interest in abalone oil, a byproduct generated during enzymatic hydrolysis, further supports this direction, as the process enables the co-production of two high-value products: hydrolysates and oil.

Furthermore, the liquid-state nature of hydrolysates facilitates more effective heavy metal removal, enhancing product safety and compliance with food-grade standards. Investigating combined-enzyme hydrolysis (alcalase + papain) and refining integrated mitigation processes will therefore be key to achieving industrial feasibility.

7.3.2 Shell

Next steps for shell valorisation should build on the three complementary pathways identified: calcium supplement, purified aragonite, and functional filler. Priority actions include regulatory engagement with FSANZ and ACNF to classify abalone shell as a natural calcium or fortification ingredient, alongside consumer acceptance testing to differentiate “marine-sourced calcium” products not only from inorganic calcium sources, but also among marine-derived alternatives (e.g., oyster shell versus abalone shell) based on compositional, structural, and functional attributes.

In parallel, it is recommended to engage key industry and research stakeholders to determine the strategic direction for future development, whether to advance high-purity aragonite separation, functional packaging applications, or alternative uses such as sustainable self-heating packaging. Among these, prioritising aragonite purification and self-heating packaging is recommended, as both offer not only strong commercial and technical potential but also added public relations and sustainability value, reinforcing industry commitment to low-waste innovation and circular economy leadership.

Collectively, these directions position abalone shell as a circular, multi-market resource with transformative applications across health, packaging, and advanced sustainable materials sectors.

7.3.3 Blood

For abalone blood, recommendations focus on stabilisation, optimisation, and regulatory translation. Immediate priorities include refining post-harvest stabilisation and hydrolysis protocols to preserve or enhance bioactivities, and verifying antimicrobial,

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antioxidant, and antiviral functions at higher concentrations using both chemical and biological assays. Engagement has been initiated with the Victorian Infectious Diseases Reference Laboratory (VIDRL) to explore collaboration on evaluating the anti-HSV-1 effects of abalone blood using infection assays in Vero cells, as outlined in the attached proposal (*Anti-HSV Effect of Abalone Blood*). This study is proposed for Phase 2 of the project and would provide critical validation of the hypothesised antiviral activity associated with abalone blood. Shelf-stability studies should be conducted to ensure reproducibility and practical scalability.

Given the favourable FSANZ classification of abalone blood as a non-traditional, non-novel food, this stream represents a low-regulatory-barrier opportunity for early-stage market development once stability challenges are resolved. Subsequent efforts should explore co-processing models with viscera hydrolysates to maximise yield, minimise waste, and create integrated marine bioactive formulations. Collectively, these steps will transform abalone blood from a discarded waste into a value-added, functional marine ingredient, supporting Australia's leadership in sustainable blue bioproduct innovation.

8. Feasibility and Stop/Go Analysis

Preliminary cost-benefit analyses were undertaken to evaluate the commercial feasibility of abalone viscera valorisation, focusing on four product formats: frozen viscera, air-dried whole viscera, freeze-dried viscera powder, and enzymatically hydrolysed viscera. These formats were selected in consultation with ACA members to reflect different levels of investment, processing capacity, and market positioning. Frozen viscera and air-dried formats were identified as low-cost, high-feasibility entry points suitable for members seeking minimal capital outlay and rapid adoption, primarily targeting the pet food sector. Freeze-dried powder, while more capital-intensive, offered improved shelf-life, product consistency, and versatility for higher-value applications in nutraceuticals and functional foods (e.g. GLM alternative). Hydrolysates, although requiring greater investment in enzymatic processing and downstream stabilisation, demonstrated the highest potential for long-term value creation due to their strong functional attributes (e.g., antioxidant and anti-inflammatory activities) and alignment with cosmeceutical and nutraceutical markets. These analyses can be requested as one of the supporting technical reports provided to the CRC and accessible on request from the CRC or the report authors (*Production Processes & Quote*).

Across all formats, cost-benefit assessments highlighted trade-offs between processing costs, scalability, and achievable market premiums. Low-cost formats offered near-term feasibility and strong stakeholder acceptance, while hydrolysates represented a high-risk, high-reward pathway requiring further optimisation of stability, heavy metal removal, and regulatory approval. Further details of this section can be found in a separate technical report (*Production Processes & Quote*).

8.1 Method

The preliminary cost-benefit analyses were undertaken in three stages. First, pathways to commercialisation were selected through consultation with ACA members and other key stakeholders' expression of interests, ensuring that processing formats aligned with industry interest, market demand, and operational capacity. Four priority formats were identified for evaluation: frozen viscera, air-dried whole viscera, freeze-dried viscera powder, and enzymatically hydrolysed viscera powder.

Second, process flow diagrams were developed for each pathway, incorporating safety control points (CCPs) based on technical assessments of practical upscaling methods. These flow diagrams integrated food safety requirements, product quality assurance, and operational feasibility, informed by both competitor benchmarking and existing seafood processing standards.

Third, costing was conducted on a pilot scale equivalent to 100kg of raw viscera input. Equipment specifications, operational requirements, and safety controls were mapped against commercial infrastructure, and quotes were obtained to estimate capital and operating costs. Potential revenue projections were collected directly from stakeholders involved in pet food, functional food, and nutraceutical markets to contextualise economic feasibility and market positioning.

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8.2 Results & Discussion

Preliminary analyses indicated a broad cost range depending on processing complexity. Overall, initial cost ranges from ~$4,000 to $185,000AUD, while potential revenues range from $2.5–130AUD/kg. Shared infrastructure and centralised processing models were recommended to reduce capital burden, particularly for advanced pathways.

These findings confirm that while frozen and air-dried formats offer immediate, low-cost opportunities, freeze-dried powder and hydrolysates provide greater long-term commercial promise, particularly in functional food and nutraceutical sectors.

8.2.1 Frozen Viscera (B-to-B)

The lowest-effort pathway, requiring minimal capital investment (~$4,000AUD). Positioned for B-to-B animal applications, this format offers modest revenue potential ($2.5–5AUD/kg) but strong feasibility, with low technical risk and immediate scalability.

8.2.2 Air-dried Whole Viscera (B-to-B/B-to-C)

A simple pathway with initial costs ~$12,000AUD. Benchmarking against air-dried, GLM suggests potential revenue opportunities in B-to-B/B-to-C non-functional pet food markets (~$50AUD/kg), though safety measures (e.g., dip tank to mitigate salt toxicosis) are critical.

8.2.3 Freeze-dried Viscera Powder (B-to-B/B-to-C)

A mid-level pathway with higher initial costs ~$100,000AUD. but access to premium B-to-B/B-to-C pet and human functional food markets. Capital investment is moderate to high, but market pricing (~$55AUD/kg), for freeze-dried marine supplements supports strong revenue potential.

8.2.4 Enzymatically Hydrolysed Viscera (B-to-B/B-to-C)

The most advanced pathway, requiring the highest initial investment (up to $185,000AUD). Positioned in high-value nutraceutical (~$130AUD/kg) and therapeutic markets, hydrolysates promise strong long-term returns, though commercial scalability hinges on overcoming stability, heavy metal, and additional food regulatory hurdles.

8.3 Conclusion

The cost–benefit assessment confirms that abalone viscera valorisation presents a tiered set of opportunities ranging from low-cost, low-risk entry points (frozen and air-dried formats) to higher-risk, higher-reward pathways (freeze-dried powder and enzymatically hydrolysed products). Frozen and air-dried viscera offer immediate feasibility with minimal investment and rapid scalability, particularly suited for pet food markets, while freeze-dried and hydrolysed formats represent long-term value creation in premium nutraceutical and cosmeceutical sectors. Although the latter require greater capital investment, stability optimisation, heavy metal removal, and regulatory approvals, they deliver substantially higher potential returns and stronger alignment with consumer demand for functional marine products.

In line with the stop/go framework outlined in the ACA proposal, the findings provide a clear commercialisation decision point: short-term “go” for crude usage pathways to generate early revenue and stakeholder engagement, alongside a conditional “go” for hydrolysates and advanced products, dependent on resolving stability and regulatory barriers. This dual-path approach ensures near-term adoption while securing long-term growth potential, supporting both ACA’s sustainability vision and industry competitiveness.

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8.4 Recommendations and Next Steps

- Prioritise near-term commercialisation of frozen and air-dried viscera as low-cost entry pathways, enabling early market adoption and stakeholder engagement in the pet food sector.
- Progress freeze-dried powder development for medium-term entry into human nutraceutical and functional food markets, leveraging its stronger shelf-life and premium market positioning.
- Integrate food safety and regulatory frameworks for human application early by preparing novel food applications with FSANZ/ACNF pathways and conducting the required safety validation
- Develop shared processing models to spread capital costs across members, reducing individual investment burden and enhancing scalability, or generate additional revenue streams for solo investors.
- Present evidence and cost-benefit analyses (*Technical Report – P&G Phase 0 Entry Assessment*) to P&G to explore alternative co-commercialisation of hydrolysates for external applications.

9. Knowledge Transfer

The project involved communication and extension to ACA members and Abalone Association of Australia (AAA) members, as well as to the seafood industry generally, via a variety of extension pathways. These pathways are summarised in the sections below. The findings and outcomes of this research will continue to be proactively shared with industry stakeholders via the ACA website, and FRDC and EFW CRC newsletters, and social media posts. A results summary PowerPoint has been prepared for use in ongoing extension activities. These activities will be developed in conjunction with the ACA. Table 1 is a summary of the extension activities of the project.

Table 1. Extension Outputs

Publication/Product	**Detail**	***Status***
HDR Theses		
M.Phil (Lynne Loo)	Improving outcomes for shell and shucking by-products in Australian abalone fisheries – a supply chain perspective	Awarded (2023)
PhD (Wing Huen (Alexis) Chung)	Utilizing Australian wild-harvested abalone viscera for functional food applications: a translation-focused approach	Awarded (2025)
Journal Articles		
Peer reviewed journal article	Chung, W. H., Coorey, R., Takechi, R., & Howieson, J. (2024). Compositional and nutritional evaluation of viscera from commercially harvested wild-caught Australian abalones (*Haliotis* spp.). *LWT*, *191*, 115590	Published
Peer reviewed journal article	Chung, W. H., Zhong, L., Takechi, R., Coorey, R., & Howieson, J. (2024). Elemental content and safety evaluation of wild-harvested Australian abalone (*Haliotis* spp.) viscera: addressing safety concerns in food waste upcycling. *LWT*, *207*, 116658	Published
Peer reviewed journal article	A comprehensive review on the impacts of natural marine substances in health and disease: the case of abalone viscera	Under Review
Peer reviewed journal article	Chung, W. H., Muurlink, O., Tan, N. S. L., Takechi, R., Coorey, R., & Howieson, J. (2025).	Published

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	Upcycled sulfated glycosaminoglycan-rich hydrolysates from abalone (*Haliotis* spp.) viscera exhibit wide spectrum antioxidant and anti-inflammatory activities. *Food Chemistry Advances*, *2026*, 101188.	
Peer reviewed journal article	Chung, W. H., Tan, N. S. L., Kim, M., Pojtanabuntoeng, T., & Howieson, J. (2024). Exploring the functional properties and utilisation potential of Mollusca shell by-products through an interdisciplinary approach. *Scientific Reports*, *14*(1), 28274.	Published
Social Media Outputs		
Food Waste Matters Podcast	S2E13c: Beyond Academia with Shan Alagappan, Alexis Chung and Melinda Nguyen	Aug 2024
FRDC Article	Pet Food and Beyond - Utilising Abalone Waste	Oct 2024
Western Australian Fishing Industry Council Video	Commercial Potential of Abalone "Waste" Research	Aug 2025
Technical Reports for Industry		
Summary of supply chain mapping results and recommendations	Compiled results sent to ACA Board and for distribution to each industry stakeholder that agreed to be interviewed.	2023
Summary and interpretation of compositional data	Individual sample results sent to each company that provided viscera samples (Western Abalone, Tasmanian Seafoods, OGA, Magic Abalone, Jonas Woolford, John Smythe)	2023
Summary of Citric acid washing trials to reduce heavy metal content	Provided to ACA Board and SARDI scientists who assisted with trials.	Oct 2025
Summary of Process Flows, Equipment costings and Cost Benefit Analysis	Provided to ACA Board	August 2025
Industry meetings		
ACA Board Briefing	Powerpoint Presentation	Sept 2021 (on-line)
ACA Board Briefing	Powerpoint Presentation	Oct 2022 (Adelaide)
ACA Board Briefing	Powerpoint Presentation	Sept 2023 (on-line)
ACA Board Briefing	Powerpoint Presentation	Sept 2024 (Hobart)
ACA/AAA/AAGA Board Briefing	Powerpoint Presentation	August 2025 (Melbourne)
FRDC 'New innovations for Seafood industry' WA case studies event	Project presentation at event	August 2023
Other Curtin Student Projects		
M.Sc (Food Science and Technology)	Preliminary viscera and blood characterisation: 4 students	2022-2024
M.Sc (Engineering) (WACC)	Separation of aragonite from abalone shell.	2025
Engineering Internship (Thai student exchange) (WACC)	Characterisation of shell and use in sustainable packaging.	2023/4

10. Final Recommendation

A series of targeted recommendations and next steps has been developed and is articulated in the detailed report. However, in summary, the proposed objectives for a possible Phase 2 project are based on the commercialisation of the opportunities informed by and highlighted in this project. Hence, the overarching recommendations of this report can be summarised as below:

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- Recommendation 1*:* Assess the technical and economic feasibility of pilot scale commercialisation of viscera and/or shell ingredient opportunities identified in Phase 1 by installation and evaluation of equipment in at least two abalone processing operations.
  Recommendation 2: Undertake further industry trials to maximise yield and product value on commercialisation questions identified in Phase 1 (defatted product hydrolysis; heavy metal amelioration; low temperature sterilisation techniques).

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APPENDIX A – Supporting Material(s)

Table 2. Proximate Composition of Roe's and Blacklip Abalone Blood

	Roe's abalone	Blacklip abalone
Moisture (%, wet basis)	95.08 ± 0.25	95.6 ± 0.02
Moisture content (%, freeze-dried basis)	3.86 ± 0.21	5.73 ± 0.13
Protein (%, dry basis)	13.02 ± 0.13	15.71 ± 0.00
Ash (%, dry basis)	68.61 ± 0.09	68.84 ± 0.12
Fat (% dry basis)	0.07 ± 0.05	0.08 ± 0.07

Table 3. Elemental Profile of Roe's Abalone Blood

	Roe's abalone
Macro-minerals (mg/kg, dry basis)	
Potassium	1184.80 ± 84.19
Sodium	26308.75 ± 2017.03
Phosphorous	37.89 ± 2.07
Magnesium	2521.81 ± 196.79
Calcium	645.69 ± 22.08
Trace elements (mg/kg, dry basis)	
Iron	6.53 ± 0.63
Zinc	ND
Copper	7.66 ± 0.85
Chromium	0.31 ± 0.04
Lead	1.40 ± 0.12
Nickel	0.74 ± 0.02

Table 4. Crystalline phase composition of molluscan shell fractions obtained following heavy liquid separation using sodium polytungstate (SPT), as determined by quantitative X-ray diffraction (XRD) analysis.

	Light Phase	Heavy Phase
Calcite (%, w/w)	87.60	1.08
Aragonite (%, w/w)	12.10	97.60
Quartz (%, w/w)	0.23	0.35
Sylvite (%, w/w)	0.09	N.D.
Amorph. (%, w/w)	0.02	1.00

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Figure 1. Separated molluscan shell fractions post-heavy liquid separation using sodium polytungstate (SPT).

The light brown upper phase represents the calcite-rich fraction, while the dense white lower phase corresponds to the aragonite-enriched fraction. The clear visual stratification highlights the effectiveness of the density-based separation technique.

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