Ref. Ares(2026)1910026 - 19/02/2026

Baltic MUPPETS

DELIVERABLE 1.5

REPORT ON THE SUSTAINABILITY OF MUSSEL FARMING AND PRODUCTION OF PET FOOD, AND ON THE VALUE OF ECOSYSTEM SERVICES

Co-funded by
the European Union

Grant agreement number	101083785
Project title	Baltic MUPPETS Baltic MUssel Products for PET foodS
Deliverable title	Report on the sustainability of mussel farming and production of pet food, and on the value of ecosystem services
Deliverable number	1.5
Deliverable version	1
Contractual date of delivery	28.02.2026
Actual date of delivery	19.02.2026
Document status	Final
Online access	Yes
Diffusion	Public
Nature of deliverable	RE- Document, Report
Work Package	1
Contributing partners	SUBNET, UTARTU, BLR
Author	Jean-Baptiste Thomas (KTH)
Editor	Contributors: Maya Miltell (SUBNET), Per Dolmer (BLR), Jonne Kotta (UTARTU) Editor: Maya Miltell (SUBNET)
Keywords	Life cycle assessment, LCA, sustainability, mussels, Baltic Sea

CONTENT

1. INTRODUCTION: PURPOSE, SCOPE AND APPROACH

Baltic MUPPETS is an EU co-funded I3 demonstration project that aims to establish viable business models based on Baltic Sea cultivated blue mussels, with a particular focus on mussel-based pet food products. This report supports project decision-making on whether, where, and how to scale Baltic blue mussel farming for pet food applications, by comparing key sustainability implications across plausible production and processing pathways. The purpose is to clarify the likely environmental performance of mussel farming and mussel-based pet food value chains, identify key hotspots and improvement levers, and describe wider ecological co-benefits and risks in a Baltic Sea context that may not be captured in standard life cycle assessment studies. The report also supports communication and market positioning by translating the most relevant environmental effects and ecosystem services into monetary terms where robust values exist, and by proposing a set of science-based and appropriately bounded "green claims" that can be made about Baltic Sea mussel pet food products.

In this report, "Baltic Sea" is used as a practical shorthand for the Baltic Sea region relevant to Baltic MUPPETS, recognising that definitions vary. Where precision matters, we follow the HELCOM "Baltic Sea Area" framing (Figure 1), which includes the Baltic Sea and its entrance area (the Danish Straits and Kattegat). This reflects the project's pilot geography, including activities in Denmark and the Kiel area (Germany). Results are therefore interpreted for the wider Baltic Sea region, including adjacent transition waters that are functionally connected to the Baltic Sea basin.

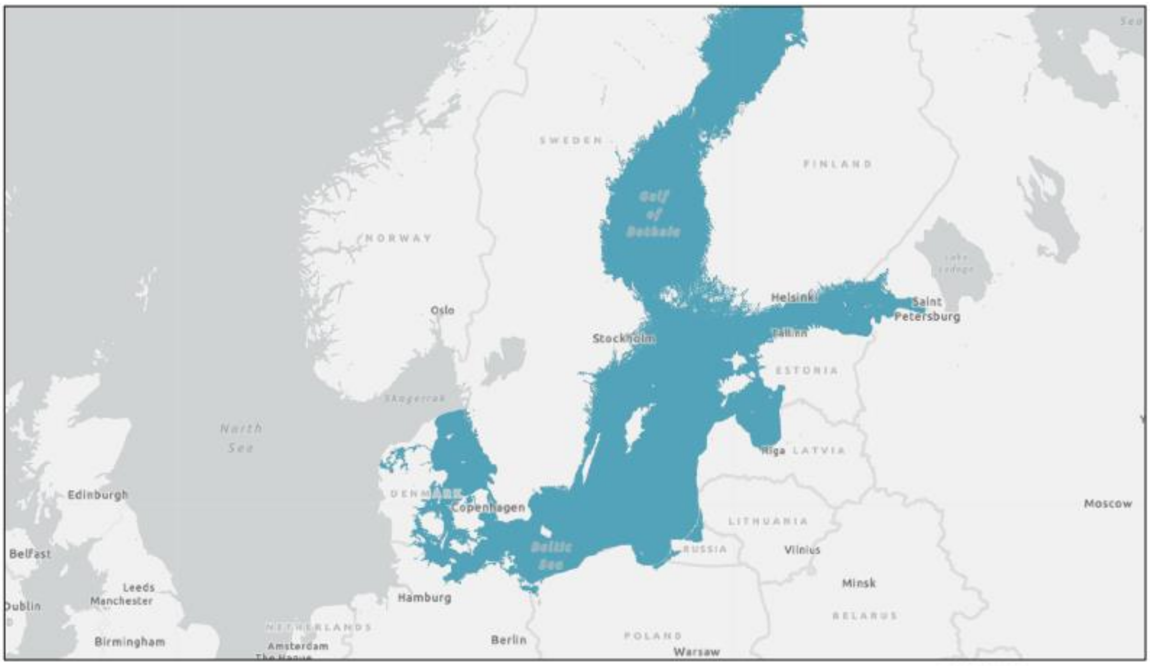


Figure 1: Geographic framing used in this report, based on HELCOM assessment sub-basins (including the Baltic Sea entrance area: Danish Straits and Kattegat). Source: HELCOM subbasins 2022 (level 2), downloaded from the HELCOM Map & Data Service (metadata catalogue record d4b6296c-fd19-462c-94d2-4c81b9313d77).

The scope of the report combines three linked lenses. First, a product and value chain lens is applied using a Life Cycle Assessment (LCA)-informed perspective that covers mussel farming and harvesting, post-harvest handling and processing, relevant transport steps, pet food manufacturing, packaging, and distribution, consistent with the available literature and the WP1 business plan assumptions. Second, a local ecosystem lens is used to cover direct environmental effects and ecosystem services at and around mussel farms, including nutrient dynamics, plankton and food-web effects, benthic impacts, and biodiversity-related outcomes and risks. Third, a societal lens is applied through monetisation and cost–benefit analysis, drawing on literature-derived values to aggregate selected impacts and services into an assessment of societal profitability.

The report is primarily a review and synthesis rather than a full new LCA model, and therefore emphasises plausible ranges, key drivers, and conditions under which outcomes are expected to change direction. Although the geographic focus is the Baltic Sea, much of the underlying LCA and biogeochemical literature is developed in marine or non-Baltic Sea settings; relevance and transferability are therefore considered throughout. Carbon performance is treated using both a life-cycle perspective on greenhouse gas emissions from inputs across the value chain and a farm-scale perspective on calcification, respiration, and sedimentation/biodeposition processes, which can materially influence interpretation and claims. This approach is based on the proposed approach by Ziegler *et al.* (submitted).

The evidence base prioritises peer-reviewed scientific literature, complemented by targeted grey literature where necessary to address Baltic-specific data gaps and practical decision needs. Grey literature is used selectively, for example to incorporate Baltic monitoring and assessment syntheses, to support system descriptions and operational assumptions where peer-reviewed sources are limited, and to provide monetary valuation inputs required for ecosystem service monetisation and cost–benefit analysis. The synthesis integrates three main evidence streams:

- LCA literature on mussel production value chains and pet food production;
- ecological literature describing local effects, benefits, and risks of mussel farms under Baltic conditions; and
- economic valuation literature providing unit values for monetisation of impacts and ecosystem services.

Across these streams, the report uses transparent scenario framing and explicit statements of confidence/limitations to distinguish robust findings from conditional insights and to avoid over-interpretation.

In this report, “sustainability potential” is interpreted primarily as environmental sustainability, assessed through an LCA-informed value chain perspective and complemented by an evaluation of local ecosystem effects. In practical terms, sustainability potential refers to the extent to which Baltic Sea mussel farming and mussel-based pet food can reduce environmental burdens relative to relevant alternative pet food protein sources, deliver ecosystem services or local environmental improvements under defined conditions, and avoid creating unacceptable local ecological impacts or trade-offs. Ecosystem services are treated as conditional and site-dependent, and the analysis therefore considers both benefits and possible disservices and risks. Societal profitability is assessed through a cost–benefit analysis that monetises selected impacts and ecosystem services using literature values and combines these with business plan assumptions from WP1. The conclusions distinguish between findings that are robust and generalisable, findings that are plausible but conditional on Baltic Sea-specific parameters, and statements that should not be framed as “green claims” due to remaining uncertainty or insufficient evidence.

2. METHODOLOGY

2.1 Literature review

This report is based on a structured literature review and evidence synthesis, complemented by analysis of internal Baltic MUPPETS documentation to ensure relevance to the project’s intended value chains and business models. First, peer-reviewed scientific literature was searched and screened to identify studies relevant to the sustainability of mussel farming and mussel-based pet food, with emphasis on:

- LCA studies of mussel production and bivalve value chains,
- LCA studies of pet food production and alternative pet food protein ingredients, and
- ecological and biogeochemical literature on ecosystem services and local environmental effects of mussel farming, particularly in brackish and Central Baltic Sea settings.

The review prioritised peer-reviewed sources, while targeted grey literature was used selectively to fill Baltic Sea-specific gaps, support parameter choices, and provide valuation coefficients for monetisation where appropriate.

Second, evidence was synthesised across these streams using a transparent, scenario-oriented approach. Findings from LCA studies were interpreted with attention to comparability, including functional units (liveweight, edible product, or protein basis), system boundaries (farmgate versus inclusion of processing, packaging, and distribution), and key modelling choices such as allocation and co-product handling. In parallel, ecological evidence was summarised to describe direction and conditionality of effects (benefits, trade-offs, and risks), with explicit consideration of Baltic Sea salinity gradients and carbonate chemistry where these influence calcification and carbon-related interpretation. Where the literature base was heterogeneous, the synthesis focused on plausible ranges and dominant drivers rather than single point estimates.

Third, internal project documentation from Baltic MUPPETS was reviewed to anchor the assessment in the project’s practical decision context and to align scenarios with the consortium’s intended implementation pathways. In particular, WP1 deliverables on business plans (D1.2), market readiness (D1.3), investment implementation, and remaining bottlenecks (D1.4) were analysed to define the relevant product routes (e.g., wet versus dried pet food pathways), scale assumptions, key processing steps, co-product opportunities (e.g., shell valorisation), and constraints affecting feasibility. Deliverable 1.7 was also relied on to provide a spatially explicit basis for interpreting production potential and ecosystem-service delivery. These project inputs were used to frame the report's system description and comparative scenarios, and to inform the cost–benefit analysis component by linking environmental effects and monetised values to the WP1 business case logic.

Finally, uncertainty was addressed using a structured scenario approach. A limited set of internally consistent scenarios were defined to reflect plausible variation in key drivers, including site productivity, scale, and value-chain configuration (for example, yield levels, processing routes, and methodological treatment of calcification-related carbon dioxide, CO_2). For ecosystem service and risk evidence, qualitative confidence judgements are applied to make the strength and limitations of the underlying literature explicit. In addition, assumptions most likely to influence results are identified, and findings are interpreted in light of plausible ranges for these parameters (including monetisation coefficients). Together, these steps support credible conclusions and "green claims" by distinguishing robust findings from conditional insights that depend on site characteristics, scale, or methodological assumptions.

2.2 Cost-benefit analysis and synthesis

Selected environmental impacts and ecosystem services have already been monetised in the literature in numerous different contexts. Part of the review extends to collect published data on the value of specific ecosystem services, as estimated in the literature. Values are compiled in Appendix C and D.

To support an indicative assessment of societal profitability from the mussel farming activities, physical quantities of carbon, nitrogen and phosphorous uptake were estimated from typical Baltic Sea farming practice, and estimated per tonne fresh weight produced mussels. These were linked to monetary unit values drawn from the peer-reviewed and authoritative grey literature. Where multiple coefficients exist, ranges were retained and transferability to Baltic conditions was assessed explicitly, with preference given to values relevant to Northern European or Baltic Sea policy contexts. Monetisation was applied selectively to avoid over-interpretation and double counting, and effects that lacked a defensible quantitative basis were retained as qualitative considerations in the overall interpretation.

Many ecosystem services listed in Appendices B–D are causally linked rather than additive. In particular, nutrient extraction (nitrogen and phosphorus removal through harvest) is an upstream regulating service that contributes to reduced eutrophication pressures and, consequently, to downstream outcomes such as improved bathing water quality, reduced nuisance algal blooms and beach fouling, and related recreational, cultural, and amenity values associated with clearer coastal waters. In this report, the nutrient-removal unit values compiled in Appendix D (and the conservative coefficient set adopted from Söderqvist *et al.* 2020) are therefore interpreted as a policy-oriented proxy for a broader bundle of water-quality welfare benefits, rather than as a stand-alone service to be summed alongside overlapping monetised endpoints. This serves to minimise the risk of double counting.

An indicative cost–benefit analysis (CBA) was then performed by combining the monetised environmental impacts (carbon emissions) and ecosystem service values (nutrient removal) with profit per kg mussel estimates from the WP1 business plans. USD and SEK inputs were harmonised to real EUR of 2024 by converting values reported in other currencies using the relevant exchange rate at the valuation year and inflating (or deflating) to 2024 using an appropriate price index. The analysis reports results as net societal value per tonne of fresh-weight mussels and, where useful, as ranges reflecting uncertainty in key coefficients and site-dependent performance. To support interpretation, monetised results are presented alongside qualitative effects not suitable for valuation, and the overall balance is discussed with explicit attention to system boundaries, potential double counting, and the conditional nature of location- and scale-dependent outcomes.

2.3 System description and scenarios

Baltic MUPPETS aims to demonstrate an emerging value chain that uses farmed Baltic Sea blue mussels as a core protein ingredient in pet food products, while also exploring the extent to which mussel cultivation can deliver ecosystem services in eutrophication-impacted coastal waters. The WP1 business planning deliverables describe a portfolio logic in which the same harvested biomass can be channelled into different product routes depending on scale, processing capacity, and market positioning, with a typical progression from small-volume, high-value products toward larger-volume products as farming and processing scale up. The business cases described have been based on the three Baltic MUPPETS pilots describing different ecological context and market readiness: Limfjorden (DK), Kiel (DE) and Västervik (SE).

At a high level, the system begins with mussel cultivation in coastal Baltic Sea waters, followed by harvesting and transport to shore, then processing into one of several ingredient/product forms for pet food. The WP1 business plans explicitly highlight that a start-up or resource-constrained operator would typically start with high-margin products such as dried dog snacks, then expand into larger-volume products (e.g., pond fish feed) as production increases and markets are developed. One illustrative pathway assumes an initial dog-snack market of approximately 10 tonnes per year (about 150,000 snacks of 65 grams), corresponding to approximately 156 tonnes of fresh mussels, followed by pond fish food at approximately 200 tonnes per year requiring approximately 1,560 tonnes of fresh mussels, with an upper illustrative scale of approximately 20,000 tonnes per year of fresh mussels when “maximum” Baltic Sea production is reached in that scenario framing. Processing steps vary by product, but the business plans and bottleneck assessment repeatedly flag shell separation (de-shelling) as a cost- and technology-sensitive step, and note that failures or high costs in processing can materially affect feasibility. In parallel, the business planning emphasises valorisation of shells as a side-stream (e.g., soil improvement, chicken feed additive), with Swedish examples including shell use for soil improvement in cooperation

Within the pet food formulation, mussels function primarily as a marine animal protein ingredient that can support product differentiation, including novel protein positioning (an alternative to conventional poultry or beef proteins, often framed for consumers as a distinctive ingredient) and “marine” positioning (associations with coastal origin and functional attributes typically linked in the market to marine ingredients, such as omega-3 content and palatability). In addition, mussels may support circularity narratives linked to local production and co-product use. The market-readiness deliverable concludes that the pet food market shows readiness for mussel-based products, but that the most viable scale-up route is likely wet-food formulations rather than dried products, because drying is energy-intensive and requires substantial capital investment (dryers, extrusion lines), undermining price competitiveness. It therefore frames a wet pathway, including minimally processed BARF-style products (Biologically Appropriate Raw Food), as the more viable route, since it avoids most drying-related capex and energy burdens and involves fewer unit operations.

Within a context of using mussel meat as an alternative protein ingredient in pet food in the comparative sustainability framing used later in the report, a small set of substitution scenarios are provided, consistent with typical pet food formulation “protein slot” choices. A pragmatic set and tentative set is:

- Poultry-based protein ingredient (common benchmark in premium pet food);
- Fishmeal / fish-based ingredient (closest functional analogue for “marine protein” positioning), and;
- Pork-based ingredient (common in many formulations, mid-range benchmark).

These are intended as reference substitution cases for interpreting literature-based LCA findings and for structuring the later cost–benefit analysis logic, rather than as an exhaustive diet-formulation model. Furthermore, as will be clear in the literature review, there are large uncertainty ranges to consider and methodological strategies that can significantly alter performance of different ingredients (e.g. valorising waste streams into pet food ingredients, allocating zero burdens), so comparisons are challenging to make in a scientifically robust manner and should be interpreted with caution.

In summary, below the scope of the project is specified:

- In scope (core system): mussel farming and harvest operations; transport from farm to processing; primary processing into pet food ingredient/product forms (wet route emphasised in WP1); packaging and distribution where the literature and WP1 assumptions allow consistent inclusion; side-stream handling of shells where relevant for scenario framing.
- In scope (local ecosystem lens): farm-adjacent effects relevant to ecosystem services and risks (nutrient removal framing, local water transparency/benthic interactions as relevant later in the report), treated as conditional and site-dependent.
- Out of scope (unless explicitly needed for interpretation): full “pet ownership” life cycle impacts (e.g., household travel, veterinary care), and downstream pet excreta management, except where referenced as contextual insights from the broader pet food LCA literature.
- Out of scope (for modelling): detailed engineering design of farms/process plants.

3. LITERATURE REVIEW

3.1 What is sustainable petfood?

Pet food sustainability has become an increasingly important topic as companion animals represent a growing share of global agricultural resource use and household environmental footprints. Sustainability concerns go far beyond the carbon footprint of kibble production, encompassing land use, biodiversity loss, eutrophication from nutrient leakage, acidification, water use, and resource demand throughout the supply chain. A key methodological challenge is that many animal-derived ingredients used in pet food are co-products of human food systems. This makes results highly sensitive to allocation rules and counterfactual assumptions about what those co-products would otherwise displace. Consequently, "sustainability" in pet food depends on system boundaries and methodological choices as much as on ingredient lists. Moreover, the life cycle of pet ownership extends beyond the product itself: packaging, distribution, and pet waste management all influence environmental outcomes (Acuff *et al.*, 2021; Yavor *et al.*, 2020).

Across recent LCAs, ingredient production, especially upstream agriculture, dominates most impact categories. In a Brazilian cradle-to-gate LCA of extruded dry dog food, Costa *et al.* (2024) found that ingredient supply associated with the formulation contributed roughly 70–90% of cradle-to-gate impacts, relative to on-site manufacturing (including extrusion), packaging, and distribution, with eutrophication, acidification, particulate matter, and climate change as key categories, emphasising that ingredient choice is the main mitigation lever. Brociek and Gardner (2025) reached similar conclusions in their analysis of 31 UK dry dog foods: When impacts were expressed per 1,000 kcal, plant-based products had the lowest impacts, poultry-based intermediate, and beef- or lamb-based the highest across all indicators. These patterns align with broader food-system trends showing ruminant ingredients as the main hotspots for land use and greenhouse-gas emissions.

System boundary choices also shape results. Yavor *et al.* (2020) assessed the entire life cycle of an average pet dog, including diet and excreta, and found that pet food dominated most categories, but freshwater eutrophication was mainly driven by urine and faeces, while faeces were an important source of freshwater ecotoxicity. This demonstrates that interventions beyond feed formulation, such as improved waste collection and treatment, can influence results. Similarly, Acuff *et al.* (2021) argue that sustainability in pet food must be addressed holistically, considering formulation, packaging, logistics, and waste management rather than focusing narrowly on ingredient origin.

Studies investigating "novel" protein sources illustrate that claimed benefits depend on real-world conditions. In a UK case study on cricket production for the live pet food market, Suckling *et al.* (2020) found that heating and energy requirements in temperate climates were dominant hotspots, while efficiency improved under a hybrid business model serving both pet and human markets. Biteau *et al.* (2025) provide a comprehensive review of the insect-farming literature and conclude that environmental advantages are often overstated because most LCAs are based on small-scale operations fed with conventional feed-grade inputs. When insects are raised on such inputs and then used as feed, they add an extra conversion step that can increase overall burdens compared with conventional animal or plant ingredients.

Jarosch *et al.* (2024) conducted a PEFCR (Product Environmental Footprint Category Rules, standardized framework for assessing the environmental impact of prepared pet food for cats and dogs)-aligned LCA of a specific canned wet vegan dog food produced in Germany, covering ingredients and packaging as well as distribution, use, and end-of-life. While removing animal-derived ingredients can lower upstream burdens relative to average meat-based alternatives, their hotspot analysis shows that primary packaging production (the tinplate steel can) is a major contributor for a wet canned product, and transport of ingredients and packaging is also non-negligible in some categories (for example smog and acidification). They also note that recycling credits at end-of-life could reduce the apparent burden of the can, but these credits are not included in the production-stage contribution breakdown they present.

Circularity and co-product valorisation emerge as promising but method-sensitive pathways. Mosna *et al.* (2021) compared a baseline scenario of conventional pet food production plus landfilling of packaged meat waste with a valorisation scenario in which the meat fraction of food waste is separated and used in pet food. Under realistic assumptions, the valorisation route reduced global warming potential and land use, though benefits depended on waste-collection efficiency and the displacement of conventional ingredients. Likewise, Sui *et al.* (2025) compared different valorisation routes for chicken co-products and found that processing all co-products into pet food had the lowest overall impacts, while incineration performed worst. However, their sensitivity analysis showed that results depend strongly on the assumed avoided products (for example soybean meal or palm oil) and on the allocation method: economic allocation yielded much lower impacts than mass allocation. Together, these studies highlight that pet food can contribute to circular bioeconomy goals when it genuinely substitutes higher-impact ingredients or waste treatments, but outcomes are contingent on transparent LCA modelling choices and realistic system boundaries.

3.2 Mussel farming LCAs

What mussel LCAs typically include and omit for climate impacts

In the mussel LCA literature, climate impacts are typically quantified from "non-biogenic" life-cycle processes that are directly represented in inventories and databases, including fuel use for farm operations and harvesting, electricity and heat use for depuration and processing where applicable, production of infrastructure materials (e.g., ropes, buoys, anchors), and sometimes packaging, transport, and distribution depending on the system boundary. By contrast, many LCAs omit or simplify farm-scale biogeochemical carbon processes that are not straightforward to represent in conventional inventories, notably carbon dioxide dynamics linked to calcification (shell formation), respiratory carbon dioxide fluxes, and the fate of organic matter and carbonate in sediments beneath farms. These omissions matter primarily when results are interpreted as evidence for "net carbon" claims rather than as conventional supply-chain footprints.

How mussels rank relative to other protein sources

Across the food LCA literature, farmed mussels (and bivalves more broadly) are consistently positioned among the lowest-impact animal-source proteins, particularly for climate impacts. Large meta-analyses and widely used syntheses show that animal products tend to have higher footprints than plant-based proteins on average, but within animal foods, bivalves are generally at the low end and can overlap with comparatively low-impact dietary options depending on production system and supply-chain choices (Poore & Nemecek, 2018; Ritchie *et al.*, 2022). In Nordic comparisons that harmonise methodological choices across common protein-rich foods, blue mussels and Pacific oysters, together with small pelagic fish such as herring, are reported among the lowest-emitting options per kg edible food, with vegetarian protein sources often close, while poultry and pork are intermediate and beef is highest (Behaderovic & Ziegler, 2020).

Drivers of variation and hotspots across mussel LCAs

A central reason mussels tend to perform well is that they are a non-fed (unfed) production system, avoiding feed production, which is frequently the dominant hotspot in fed aquaculture and terrestrial livestock supply chains (Gephart *et al.,* 2021; Jones *et al.,* 2022; Langdal *et al.*, 2025). Even so, mussel LCA results are not “one number”: they vary substantially with farming context and practice, inventory assumptions, and methodological choices, including functional unit, allocation, and which impact categories are covered (Langdal *et al.,* 2025). In a review that harmonised published LCAs of blue mussel aquaculture, the average global warming potential was reported as 263 ± 179 kg carbon dioxide equivalents (CO_2e) per tonne whole mussel, with a wide range across studies (Langdal *et al.*, 2025). This variability is consistent with farm-level evidence from multi-site assessments across the northeast Atlantic, where cradle-to-farmgate non-biogenic climate impacts were estimated in the order of 150–450 kg CO_2e per tonne liveweight (production-weighted mean around 270 kg CO_2e per tonne liveweight) and where hotspots were typically linked to fuel use for operations and harvesting and, depending on the system, infrastructure materials such as ropes/lines, buoys, and anchoring components (Ziegler *et al.,* submitted). For other impact categories, infrastructure can also be influential, and some operational practices can drive trade-offs; for example, reseeding-related practices such as cotton socking can increase eutrophication- and land-use-related burdens even when greenhouse gas emissions are comparatively low (Ziegler *et al.*, submitted). Beyond the farmgate, downstream processing and product format can materially shift climate impacts, with evidence from the Spanish mussel food chain indicating higher footprints for more processed products (e.g., pickled/canned) and lower footprints for less processed forms (e.g., frozen), reflecting the importance of industrial processing, packaging, and logistics (Saralegui-Díez *et al.*, 2026).

Comparability issues: functional unit, boundaries, and multi-functionality

Interpretation of “equivalence” across proteins also depends strongly on the basis of comparison. Rankings can shift depending on whether results are expressed per kg liveweight, edible meat, or protein, and bivalves may appear less favourable on a per-protein basis because their edible protein density differs from many meats (Behaderovic & Ziegler, 2020). In addition, converting farmgate impacts to edible product can substantially increase impacts per kg edible meat when edible yield assumptions are lower, which reinforces the need to state the functional unit and yield assumptions transparently when making comparative claims (Ziegler *et al.,* submitted). A further source of variation is the inclusion (or omission) of downstream processes such as depuration, processing, packaging, and distribution, as well as differences in assumed energy mixes and operating conditions across regions and supply chains (Saralegui-Díez *et al.*, 2026); Ziegler *et al.*, submitted). Finally, mussel studies differ in how they treat co-products and multi-functionality (e.g., shell vs. meat, and whether nutrient-removal functions are credited), which can further influence results and comparability across studies (Langdal *et al.,* 2025).

Table 1: Side-by-side edible-basis climate values (non-biogenic, biogenic shell-formation CO_2, combined), comparing Gephart et al. (2021), Bianchi et al. (2022), and Ziegler et al. (submitted).

Source (as cited)	**Non-biogenic life-cycle GHG (kg CO_2e/kg edible)**	**Biogenic CO_2 from shell formation (kg CO_2e/kg edible)**	**Combined (kg CO_2e/kg edible)**
Gephart *et al.* (2021)	1.40*	Not included*	1.40
Bianchi *et al.* (2022)	1.35*	Not included*	1.35
Ziegler *et al.* (submitted; NE Atlantic farmgate)	0.77	0.53†	1.30†

* *Exclude shell formation emissions*

† "Combined" is a *theoretical worst-case* where *100% of biogenic CO_2 from shell formation reaches the atmosphere* (1.3 kg CO_2e/kg edible). The biogenic column here is calculated as 1.30 − 0.77 = *0.53*.

Table 1 clarifies these comparability issues by presenting edible-basis climate values from widely cited sources side-by-side while separating non-biogenic life-cycle emissions (e.g., fuels, electricity, infrastructure, processing) from biogenic carbon dioxide linked to shell formation. The global edible-basis values reported by Gephart *et al.* (2021) and Bianchi *et al.* (2022) are higher than the non-biogenic edible-basis estimate in Ziegler *et al.* (submitted), but they are close to Ziegler *et al.*'s combined value when shell-formation carbon dioxide is included under a conservative (worst-case) assumption. This illustrates that part of the apparent discrepancy across sources is driven by differences in scope and accounting, rather than indicating fundamentally inconsistent evidence. In particular, Ziegler *et al.* (submitted) explicitly separates climate impacts into non-biogenic life-cycle emissions and an additional shell-formation term, whereas global syntheses commonly report a single edible-basis footprint and typically exclude calcification-related carbon dioxide dynamics in their reported mussel values (Gephart *et al.*, 2021; Bianchi *et al.*, 2022; Ziegler *et al.*, submitted). Differences may also arise from the representativeness of underlying production systems and supply chains: Gephart *et al.* (2021) and Bianchi *et al.* (2022) draw on broad global datasets and assumptions that may implicitly reflect a wider range of farming practices, processing steps, energy mixes, and transport distances than the specific northeast Atlantic farm cases assessed by Ziegler *et al.* (submitted). More generally, variation across these sources can be explained by:

- System boundary choices (farmgate vs inclusion of processing/packaging/cold-chain);
- functional unit and edible yield assumptions;
- allocation and co-product handling, and;
- whether carbon chemistry linked to calcification is included and how its atmospheric fate is treated (Langdal *et al.*, 2025; Ziegler *et al.*, submitted).

Ziegler *et al.* (submitted) provides the core framing adopted in this report: climate performance is interpreted by separating (i) conventional non-biogenic life-cycle emissions driven by operational inputs and infrastructure from (ii) carbonate-system carbon dioxide dynamics associated with shell formation, and then evaluating how alternative assumptions about atmospheric exchange change the combined result. The manuscript's key messages are that non-biogenic farmgate impacts can be low but variable across sites and technologies, that calcification-related carbon dioxide can be material relative to non-biogenic emissions under conservative assumptions, and that meaningful mitigation levers exist primarily within the non-biogenic component (e.g., longer material lifetimes, reduced losses, electrification), while "net carbon" narratives require additional site-specific evidence beyond standard LCA practice.

Finally, for mussels specifically, a key caveat in "rule-of-thumb" comparisons is that many LCAs focus on energy and material inputs and do not consistently incorporate carbon dioxide dynamics linked to calcification and carbonate chemistry. Broader assessments of "climate-friendly seafood" highlight that bivalve mariculture involves both greenhouse gas sources and potential sinks and that variability in biogeochemical processes complicates simple climate narratives. In the northeast Atlantic farm assessments, carbon dioxide potentially generated in seawater shell formation was calculated to be on the order of approximately 187–202 kg carbon dioxide per tonne liveweight; however the subsequent fate of the carbon dioxide is uncertain, and production in seawater is not equivalent to atmospheric emission. Under conservative (pessimistic) assumptions about atmospheric release, can substantially increase total climate impacts and in some cases rival or exceed the non-biogenic life-cycle emissions (Ziegler *et al.*, submitted). At the same time, scenario analyses indicate meaningful mitigation potential within the conventional (non-biogenic) life-cycle inventory through measures such as extending material lifetimes, reducing harvest losses, and electrification, with the magnitude of reductions depending on the electricity mix (Ziegler *et al.*, submitted). Taken together, the literature supports mussels as a low-impact protein option in many contexts, but also indicates that robust comparisons and defensible climate claims require careful attention to functional units, downstream processing choices, and the treatment of shell-formation carbon.

Interpreting mussel farming in terms of net carbon benefits requires going beyond conventional LCA inventories. Shell formation can increase dissolved inorganic carbon (DIC) in surrounding water during calcium carbonate precipitation, respiration returns carbon dioxide through metabolism, and filtration transfers organic matter to sediments via faeces and pseudofaeces. The biogeochemical consequences of this deposition are context dependent. In sheltered, high-salinity settings with rapid bivalve growth, local organic accumulation and elevated benthic oxygen demand have been reported in some systems. By contrast, observations from Baltic Sea farms indicate that organic enrichment beneath farms is not systematic and may be absent or even reversed, potentially due to hydrodynamic exposure, modest growth rates in brackish conditions, and benthic community responses that enhance sediment oxygenation and nutrient retention. Spatial modelling further supports strong regional constraints on mussel growth and shell formation along the Baltic salinity gradient, implying that deposition-related effects cannot be generalised across the basin. For this reason, the report treats carbon claims conservatively: LCA results are used to compare non-biogenic supply-chain footprints, while net carbon narratives are discussed as conditional and site-dependent, with particular caution regarding the fate of calcification-related carbon dioxide in seawater and its (often unknown) air–sea exchange.

3.3 Wider ecological effects, ecosystem services, and risks in the Baltic

Calcification in brackish conditions

Calcification (calcium carbonate precipitation) is intrinsically linked to the seawater carbonate system: when an organism precipitates calcium carbonate ($CaCO_3$), it shifts carbonate equilibria and releases carbon dioxide into the surrounding water. Importantly, this carbon dioxide release is not stoichiometrically 1:1 with calcium carbonate formed; it depends on the buffering capacity (alkalinity) of the water. A classic synthesis expresses this as the ratio of carbon dioxide released per calcium carbonate precipitated, which is about 0.6 in seawater but approaches 1 in freshwater, because lower buffering means more of the carbonate-system perturbation expresses itself as carbon dioxide (Frankignoulle *et al.*, 1995). From a Baltic Sea perspective, this matters because it is a brackish, marginal sea with carbonate chemistry that can be markedly different from fully marine waters and can approach low saturation states seasonally and regionally. For example, Tyrrell *et al.* (2008) report that the Baltic Sea can become undersaturated (or nearly so) in winter with respect to both aragonite and calcite, which implies conditions where shell formation is more difficult and where dissolution risk increases (Tyrrell *et al.*, 2008). Long-term projections similarly highlight the potential for wider undersaturation in parts of the Baltic Sea as acid–base conditions evolve (Omstedt *et al.*, 2012).

At the organism level, Baltic Sea-relevant experiments show that low salinity constrains calcification largely through reduced calcium availability and less favourable carbonate chemistry rather than “salinity stress” alone. Thomsen *et al.* (2018) demonstrate that larval shell formation in Baltic Sea mytilids becomes calcium (Ca^{2+}) limited around 3 micromole (mM), a threshold that corresponds to salinities below approximately 7–8 promille in parts of the Baltic Sea, and they also show sensitivity to lowered DIC, linking performance to aragonite saturation state and related carbonate-system predictors (Thomsen *et al.*, 2018). For later life stages, Sanders *et al.* (2018) find that mussels at 6 practical salinity units (psu) exhibit reduced calcification and, crucially, higher energetic costs of calcification (reported as roughly 2–3 times higher under low salinity/low temperature conditions), which constrains growth and implies that Baltic Sea mussels may often calcify more slowly or allocate proportionally more energy to shell formation than conspecifics in higher-salinity waters (Sanders *et al.*, 2018).

A recent regional modelling study by Vaher *et al.* (2024) complements these experimental insights by mapping the carbon immobilised in shells (as calcium carbonate) for farmed Baltic blue mussels using a Dynamic Energy Budget (DEB) model adapted to include biocalcification. The study explicitly notes that the analysis does not quantify whether mussel farming is a net carbon source or sink, which would require a full carbon budget and life-cycle assessment of cultivation and harvesting. Instead, the mapped indicator represents the long-term immobilisation of carbon in shells and shows strong spatial heterogeneity aligned with the Baltic salinity gradient, with highest values in the outer/western region (Danish Straits, Belt and Kattegat) and much lower values in central and inner sub-basins.

Taken together, the literature supports three implications for interpreting calcification-related carbon flows in the Baltic. First, per mole of calcium carbonate formed, carbon dioxide release to surrounding water can be higher in lower-buffer waters (Frankignoulle *et al.*, 1995). Second, the same Baltic conditions that increase the potential carbon dioxide release per unit calcium carbonate can also reduce calcification rates and shell production, lowering calcium carbonate formation per kg harvested mussel relative to fully marine settings. Third, regional modelling of shell-carbon immobilisation indicates that the potential magnitude of shell formation is strongly site-dependent and follows the salinity gradient, with the highest shell-carbon capture potential in the outer Baltic region (Danish Straits/Belt/Kattegat) and substantially lower values in central and inner sub-basins (Vaher *et al.*, 2024). The net outcome is therefore site- and season-dependent and is best treated as a sensitivity range anchored in Baltic carbonate chemistry (the seawater calcium-carbonate saturation states, Ca^{2+} and DIC availability), while avoiding unqualified “carbon capture” claims unless supported by site-specific evidence and monitoring.

Ecosystem services from mussel cultivation in the Baltic Sea

Mussel cultivation can deliver several ecosystem services, but the Baltic Sea’s brackish conditions shape both the magnitude of benefits and the nature of trade-offs. The most consistently highlighted regulating service is nutrient extraction, where harvesting removes nitrogen and phosphorus contained in mussel tissue (and to a lesser extent shell), thereby contributing to eutrophication mitigation (Kotta *et al.*, 2020; Timmermann *et al.*, 2019). Filtration can also reduce suspended particles and phytoplankton locally, potentially improving water clarity and related coastal values, although the strength of this signal depends on site hydrodynamics, background productivity, and farm scale (Kotta *et al.*, 2020).

A key Baltic Sea-specific message is that service delivery is strongly constrained by the salinity gradient. Owing to a lack of specific studies focusing on this, it is difficult to be specific; however it is clear that generally speaking, Brackish conditions often reduce growth rates, mussel size, and yield per unit area, which in turn lowers potential nutrient removal per hectare and per year relative to many fully marine cultivation settings (Buer *et al.*, 2020; Vaher *et al.*, 2024). Mechanistically, limitations are not only osmotic. Low salinity in parts of the Baltic co-occurs with carbonate system and calcium constraints that can increase the energetic costs of shell formation and thereby limit growth and calcification (Sanders *et al.*, 2018; Sanders *et* *al.*, 2021). These constraints also influence discussions of carbon-related benefits, because shell formation is an important component of any “carbon capture” framing. Regional modelling suggests that carbon capture potential from farmed blue mussels is spatially heterogeneous and generally stronger in more saline areas of the Baltic region (Vaher *et al.*, 2024).

Supporting services are frequently described, but evidence is often more context-specific than for nutrient extraction. Farm infrastructure (ropes, floats, lines) provides hard substrate and three-dimensional structure that can act as habitat for epibenthic communities and associated fauna, potentially increasing local biodiversity. However, the Baltic Sea’s lower salinity and different species pools often mean communities differ from those in higher-salinity systems, and net biodiversity outcomes depend on farm density, siting, and background environmental sensitivity (Falconer *et al.*, 2023; Maar *et al.*, 2023).

In non-brackish settings, the same service mechanisms apply, but higher salinity and more favourable carbonate chemistry often support faster growth and higher yields, which can increase nutrient extraction per unit farm area and strengthen provisioning services such as food production. This is one reason that, outside the Baltic, mussel farming is more commonly justified through food markets in addition to environmental co-benefits, whereas in much of the Baltic Sea it is frequently discussed as a mitigation measure whose economics depend on yields, market outlets, and policy design (Filippelli *et al.*, 2020; Gren *et al.*, 2018).

Potential adverse effects and trade-offs

A frequently discussed potential adverse pathway, primarily documented in sheltered, high-salinity systems, is biodeposition leading to local organic enrichment. Mussels transform filtered material into faeces and pseudofaeces that can increase sedimentation beneath farms, raising sediment oxygen demand and altering benthic nutrient cycling. However, available observations from Baltic Sea farms suggest such enrichment is not typical under prevailing exposed, brackish conditions and may in some cases be reversed. In oxygen-sensitive coastal systems, this can increase the risk of local hypoxia if farms are sited in poorly flushed or stratified areas, or if production exceeds local carrying capacity (Maar *et al.*, 2023). Importantly, the same modelling work highlights a scale-dependent trade-off: at farm scale, increased sediment fluxes can reduce apparent mitigation efficiency, while at basin scale, reduced phytoplankton and detritus can lower broader sedimentation and yield net nutrient reductions. This makes siting and scaling central to whether outcomes are perceived as beneficial or harmful (Maar *et al.*, 2023).

Trade-offs can also arise through ecological interactions and community shifts. Organic enrichment may favour opportunistic benthic taxa at the expense of sensitive species, and intense filtration can, in some contexts, affect food availability for other suspension feeders. Farm structures can concentrate predators and modify local food webs, and they may also facilitate biofouling communities that create operational and ecological challenges. While these effects occur in both brackish and marine settings, the Baltic Sea’s frequent oxygen limitations and eutrophication legacies heighten concern about local benthic impacts, reinforcing the need for conservative density limits, adequate depth, and good flushing conditions (Falconer *et al.*, 2023; Timmermann *et al.*, 2019).

Areas of uncertainty, safety, and regulatory risk

Uncertainties remain in translating site-level observations into robust, scalable claims. Nutrient extraction rates vary with growth, tissue content, mortality, and harvest timing, and net effects depend on whether local sediment feedbacks offset part of the water-column benefit. Climate-driven changes in temperature, stratification, and salinity could shift both production potential and environmental sensitivity, which complicates long-term planning (Buer *et al.*, 2020; Sanders *et al.*, 2021).

Safety and regulatory issues are particularly important where mussels are intended for food or feed, and they can constrain scaling even when environmental benefits are plausible. Mussels bioaccumulate contaminants and are widely used as bioindicators, but this also means that harvested biomass may face restrictions depending on site-specific contamination profiles. Baltic Sea studies document co-occurrence of chemical contamination and micro litter exposure in mussels, highlighting the need for careful site selection, routine monitoring, and conservative end-use pathways when contaminants are present (Kuprijanov *et al.*, 2024). Microplastics and microfibres are also reputational risks for consumer-facing markets, and they can trigger additional quality assurance requirements in value chains.

Harmful algal blooms and associated toxins are another constraint. Monitoring of multiple toxin groups in Baltic Sea mussel farms has shown seasonal toxin presence in mussel tissue, even when concentrations remain below available guideline or regulatory thresholds in the studied period, underscoring that routine toxin surveillance is needed to manage harvest windows and substantiate product safety claims (Olofsson *et al.*, 2025). These risks are not unique to the Baltic, but brackish conditions and cyanobacterial bloom dynamics shape exposure profiles and may complicate communication of “clean” or “toxin-free” claims.

Finally, regulatory compliance can be decisive. EU hygiene and official control frameworks for products of animal origin, including live bivalve molluscs, establish requirements that interact with area classification, monitoring, and competent authority controls, which can raise transaction costs and limit operational flexibility (European Commission, 2019; European Parliament and Council, 2004). In practice, these governance constraints mean that ecosystem-service narratives should be paired with transparent discussion of monitoring capacity, end-use options, and the evidentiary basis for any environmental claims, especially in the Baltic Sea where service delivery is strongly site-dependent and safety profiles can vary sharply over short spatial scales.

4. MONETISATION AND SOCIETAL PROFITABILITY

This section translates selected environmental impacts and ecosystem services associated with Baltic mussel farming and mussel-based pet food into monetary terms, and uses these values to conduct a simplified Cost-Benefit Analysis of societal profitability. Here, "societal profitability" is used in the cost–benefit sense of net social welfare, defined as the monetised value of benefits minus costs borne by society (including environmental externalities), rather than the private profitability of a producer.

The intention is not to produce a definitive economic appraisal, but to provide a synthesis that supports decision-making and communication. Monetisation is therefore applied selectively to those impacts and services for which peer-reviewed or authoritative valuation coefficients exist and can be meaningfully transferred to a Baltic Sea context, while explicitly documenting value ranges, key transfer assumptions, and sources of uncertainty.

4.1 Monetisation of nutrient and carbon uptake

Valuing marine ecosystem services in monetary terms involves translating changes in ecological conditions into changes in human welfare or avoided societal costs. The studies in Appendices C and D illustrate three main valuation pathways. First, welfare-based methods estimate people's willingness to pay (WTP) for environmental improvements, either from revealed preferences (e.g., the travel cost method estimating consumer surplus for coastal recreation) or from stated preferences (e.g., contingent valuation and contingent behaviour approaches eliciting WTP or changes in trips under alternative water-quality scenarios). This is the logic underlying the recreation and eutrophication benefit estimates summarised in Appendix C (Ahtiainen *et al.*, 2014; Ahtiainen *et al.*, 2022; Bertram *et al.*, 2020; Czajkowski *et al.*, 2015; Nieminen *et al.*, 2019; Risén *et al.*, 2017). Second, cost-based methods approximate value using the costs of achieving an equivalent outcome through engineered measures, for example using wastewater treatment abatement costs per kg nitrogen or phosphorous removed, or shadow prices inferred from treatment cost structures (Hautakangas *et al.*, 2014; Hernández-Sancho *et al.*, 2010), plus benchmarks reported from AKTiiVS (2022) and Centrum Balticum, 2018) in Appendix D). Third, some entries reflect synthesis/compilation of unit values from multiple sources (e.g., Hasselström *et al.*, 2020) as reported), which is often a pragmatic route for CBAs when primary valuation is out of scope.

The wide variation in reported values, especially for nutrient regulation, is expected and does not imply that one estimate is "right." Values differ because studies often value different endpoints (e.g., "kg nitrogen removed" as an engineering outcome versus WTP for reduced eutrophication symptoms), use different baselines and marginal changes (average costs versus marginal costs; small improvements versus achieving policy targets), and rely on different assumptions about the ecological production function linking nutrient changes to water clarity, blooms, biodiversity, or recreation. Variation is amplified by site heterogeneity in the Baltic Sea (hydrodynamics, salinity gradients, oxygen conditions), by differences in time horizon and discounting, and by benefit transfer choices when applying estimates from one country or context to another (as is done explicitly in Appendix C). Finally, there are common practical challenges: Avoiding double counting across services, maintaining consistent units (kg nitrogen vs kg phosphorous vs phosphate equivalents vs “per person per year”), and being transparent about whether the valuation reflects welfare gains (what society would pay) or policy/technology costs (what society would need to spend). Standard guidance therefore recommends presenting value ranges, documenting transfer assumptions, and using sensitivity analysis rather than relying on single point estimates (Hanley *et al.*, 2009; Johnston *et al.*, 2015).

In the beach-cast CBA conducted by Söderqvist *et al.* (2022), the carbon side uses a Swedish CBA social cost of carbon of SEK 7 per kg carbon dioxide, which corresponds to roughly SEK 25.7 per kg carbon (about USD 3 or EUR 2.76 per kg carbon when expressed per kg of elemental carbon). For nutrient removal, the paper’s mean benefit value is USD 38 per kg reduced phosphate equivalents (PO_4-eq). Using the conversion factors stated in the paper (1 kg nitrogen = 0.42 kg PO_4-eq; 1 kg phosphorous = 3.07 kg PO_4-eq), this implies average benefits of about USD 16 or EUR 14.7 per kg nitrogen removed and about USD 116.7 or EUR 107.4 per kg phosphorous removed.

Relative to the tables compiled in Appendix C and D, these beach-cast nutrient values sit in the same general order of magnitude as some of the abatement-cost benchmarks (e.g., approximately EUR 10 per kg nitrogen and EUR 100 per kg phosphorous-type values), but they are far below the very high mussel-farm nutrient removal values reported in parts of the Baltic mussel ecosystem-service valuation literature (which can reach the EUR 100–1000 per kg nitrogen and EUR 1000–10,000 per kg phosphorous range depending on assumptions and site productivity). The principle reason is that Söderqvist *et al.* (2022) are monetising nutrient reductions using policy/valuation coefficients linked to eutrophication damage/abatement framing (via PO_4-eq and related conversion), whereas mussel farm valuation ranges often reflect replacement costs and feasibility constraints specific to mussel production in low-salinity Baltic Sea conditions, where achieving each kg of removal can be much more resource-intensive and sensitive to yield and scale. On the carbon side, the beach-cast paper’s approximately USD 3 per kg carbon (via SEK per kg carbon dioxide) is essentially a standard “social cost of carbon”-style unit value, while several entries in the earlier tables are welfare totals (million/billion EUR per year) or recreation WTP rather than directly comparable per kg emissions values.

4.2 Cost–benefit analysis framework

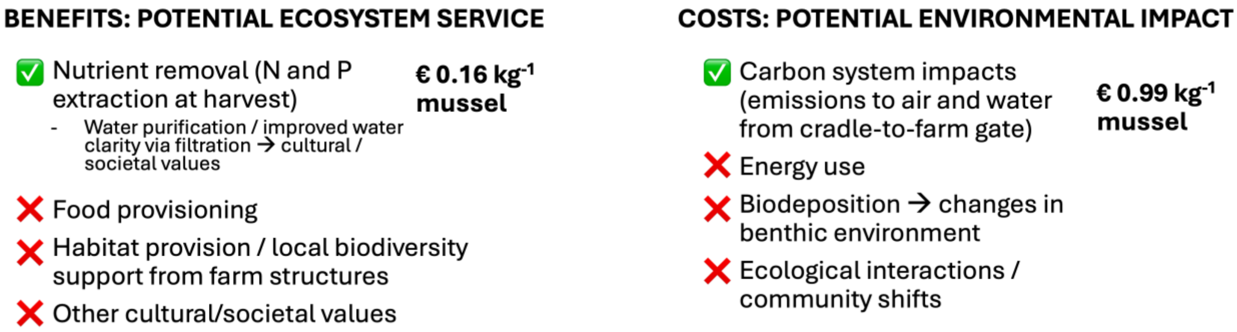
The CBA compares the societal costs and benefits of producing mussel-based pet food products against relevant counterfactual scenarios in which mussels are not used, and pet food protein demand is met using alternative ingredients. The analysis is structured around three components:

- Private production costs and revenues associated with farming, processing, and product manufacture;
- external environmental costs associated with life-cycle impacts; and
- external environmental benefits associated with ecosystem services, primarily nutrient extraction and related eutrophication mitigation.

Table 2: Profit per kg mussel across nine product types explored in Baltic MUPPETS, estimated across three scales of production. Reproduced from Deliverable 1.1 Annex 2, Table 15.

PRODUCT	**Profit per kg mussel (€)**		
Production scale (t/year)	**400**	**2,750**	**10,000**
Dog snacks (recipe Ecopelag)	3.22	4.41	4.68
Pond fish feed from dried mussel meat	-0.95	0.24	0.50
Dried mussel meat for chicken	-1.38	-0.19	0.08
Fertilizer whole mussel	-1.14	0.06	0.32
Chicken feed (cocked and dried, including shell)	-0.85	0.35	0.61
Mussel shells (as chicken food additive)	-1.25	-0.06	0.21
Raw mussel meat ("BARF")	-1.02	-0.07	0.19
Raw mussels unprocessed	-0.27	0.35	0.54
Dog / cat food (recipe CAU)	-1.40	-0.21	0.06

Private production costs and revenues are directly aggregated into profit per kg mussel in Table 15 of D1.1 Annex 2, reproduced in Table 2 above. External environmental costs and benefits are reviewed in the previous section and values per unit nitrogen, phosphorous or carbon removed or emitted are taken from there. Specifically, given the similarity with the Söderqvist *et al.* (2022) study, those same relatively conservative values are reused in the present calculation, though it should be noted that very wide ranges could be used instead. Nitrogen and phosphorous content of Baltic mussel is assumed to be 0.71% and 0.065% of wet weight mussel (Hedberg *et al.*, 2018). Thus, an average of 0.0071 kg nitrogen and 0.00065 kg phosphorous are assumed to be removed from the Baltic per kg of mussel, equivalent to a societal value of EUR approximately 0.1 for nitrogen removal per kg of mussel, and approximately EUR 0.06 for phosphorous removal per kg of mussel, when using the Söderqvist *et al.* (2022) recommended values. Thus, one can assume that the nutrient removal is equivalent to benefit value for society of approximately **EUR 0.16 per kg mussel**. Carbon emissions of 1.3 kg carbon dioxide equivalent (or 0.36 kg elemental carbon) per kg are taken from Ziegler *et al.* (Submitted), equivalent to a societal cost of approximately **EUR 0.99 per kg mussel.**



BENEFITS: POTENTIAL ECOSYSTEM SERVICE

- ✅ Nutrient removal (N and P extraction at harvest) — **€ 0.16 kg^{-1} mussel**
    - Water purification / improved water clarity via filtration → cultural / societal values
- ❌ Food provisioning
- ❌ Habitat provision / local biodiversity support from farm structures
- ❌ Other cultural/societal values

COSTS: POTENTIAL ENVIRONMENTAL IMPACT

- ✅ Carbon system impacts (emissions to air and water from cradle-to-farm gate) — **€ 0.99 kg^{-1} mussel**
- ❌ Energy use
- ❌ Biodeposition → changes in benthic environment
- ❌ Ecological interactions / community shifts

Figure 2: Summary of potential ecosystem services (benefits) and environmental impacts (costs) associated with Baltic mussel farming. Checkmarks (✓) indicate items quantified and monetised in the cost–benefit analysis, expressed as EUR per kg mussel. Crosses (✗) indicate effects identified in the literature but treated qualitatively (not monetised) due to context dependence and/or limited data, including water-clarity and cultural benefits, food provisioning, habitat/biodiversity effects, energy use, biodeposition and benthic changes, and broader ecological interactions.

4.3 Sensitivity checks and dominant assumptions

As aforementioned, the monetary value of nitrogen and phosphorous removal varies in the literature by orders of magnitude. In the present estimates, a conservative approach is considered using policy/valuation coefficients linked to eutrophication damage/abatement framing. However other valuation studies, employing methods that reflect replacement costs and feasibility in the Baltic Sea, could give a value per kg nitrogen or phosphorous removal that are ten times higher. As such, it is not unreasonable to assume that the nitrogen and phosphorous removal benefit value for society of about EUR 0.16 could also be as high as EUR 1.6 per kg mussel, reflecting these wider ranges.

Furthermore, the nutrient removal potential of mussel farming has long been debated in the literature, from a feasibility point of view, but also due to possible pseudo-faeces accumulation under/down current from mussel farms, resulting in a local intensification of eutrophication. This is not considered in the present study owing to a lack of evidence that this takes place in practice, notably given that mussel farms are positioned strategically to mitigate accumulation, and to ensure that nutrients are dispersed over wider areas, reducing pressures on local carrying capacity. However, this should be noted and considered in futures studies considering the value of nitrogen and phosphorous removal, specifically in the context of farming bivalves in sensitive and/or eutrophic conditions.

These conservative estimates are far below the very high mussel-farm nutrient removal values reported in parts of the Baltic Sea mussel ecosystem-service valuation literature. Some studies report values on the order of EUR 100–1000 per kg nitrogen and EUR 1000–10000 per kg phosphorous, depending on valuation method, assumptions and site productivity. The principal reason is that Söderqvist *et al.* (2022) are monetising nutrient reductions using methods that policy/valuation coefficients linked to eutrophication damage/abatement framing (via PO_4-eq and related conversion), whereas mussel-farm valuation ranges often reflect replacement costs and feasibility constraints specific to mussel production in low-salinity Baltic Sea conditions. In such contexts, achieving each kg of nutrient removal can be more resource-intensive and highly sensitive to yield and scale.

Beyond the quantified nutrient and carbon items included here, several “other” ecosystem-service and risk dimensions could materially influence societal profitability but are not robustly monetised due to data gaps and high context dependence. Potential additional benefits include local improvements in water clarity and recreation value via filtration, habitat provision and associated biodiversity effects around farm structures, and possible contributions to local circularity through shell valorisation. However, each of these pathways depends strongly on siting, farm density, hydrodynamics, background eutrophication status, and the ecological production functions linking farming to human welfare outcomes. Similarly, there are potential disservices that can erode benefits, notably biodeposition-driven organic enrichment and sediment oxygen demand, which may increase local hypoxia risk in poorly flushed areas. These local effects are precisely where “average” values transferred from the literature are least reliable, and where double counting risks are highest (e.g., valuing both nutrient removal and downstream welfare improvements without a consistent production function).

Key data gaps that limit stronger conclusions include:

- Baltic-specific, farm-scale measurements linking production intensity to net nutrient effects when sediment feedbacks are included;
- consistent and comparable data on edible yields, processing routes, and energy use for the WP1-relevant product pathways (especially wet/BARF versus dried routes);
- robust monitoring-based evidence on contaminant and biotoxin variability at candidate farming sites and the resulting constraints on end-use pathways, and;
- improved treatment of carbon chemistry and shell-formation carbon dioxide in brackish conditions, including better bounds on the fate of calcification-related carbon dioxide and the balance between remineralisation and longer-term burial beneath farms.

Addressing these gaps would not necessarily change the qualitative conclusion that Baltic mussels can be environmentally beneficial, but it would materially improve confidence in monetised ranges, reduce uncertainty in “green claims,” and help identify where policy design (e.g., nutrient-credit schemes, siting guidance, monitoring requirements) can most effectively de-risk investment and scaling.

5. SYNTHESIS, SUSTAINABILITY AND POTENTIAL GREEN CLAIMS

Using conservative valuation coefficients and typical Baltic Sea mussel nutrient contents, the monetised benefit of nutrient extraction is estimated at about EUR 0.16 per kg fresh mussel (approximately EUR 0.10 from nitrogen and EUR 0.06 from phosphorous removal). This suggests that, if nutrient-removal payments were feasible through policy instruments or local schemes, the ecosystem-service contribution could represent a small but tangible additional revenue stream for operators. Relative to the profit-per-kg mussel ranges reported across product routes and scales in D1.1 (Annex 2, Table 15), reproduced below in Table 3, ecosystem service values are not high enough relative to profit to be decisive on its own, however they are high enough also not to be negligible. The percentage increase is significantly higher in Table 3 for lower value products per kg mussel (e.g. mussel shells), while the effect on higher value products (e.g. dog snacks) is more marginal.

Please note that ecosystem service value estimates are intentionally conservative. The literature indicates that nutrient-regulation values can vary by orders of magnitude depending on valuation method (e.g., WTP versus abatement/replacement cost), baseline and marginal change assumptions, and Baltic Sea-specific productivity and feasibility constraints. The values in Table 3 below should therefore be interpreted as an illustrative lower-bound, suitable for cautious decision support rather than as a definitive economic value.

Table 3: Profitability including payment for nutrient removal services, per kg mussel and across nine product types explored in Baltic MUPPETS, estimated across three scales of production.

PRODUCT	**Profitability (€ per kg mussel) including payment for nutrient removal, including percentage increase relative to profit without nutrient payment**					
Production scale (t/year)	400		2750		10000	
Dog snacks (recipe Ecopelag)	3.38	*5%*	4.57	*4%*	4.84	*3%*
Pond fish feed (from dried mussel meat)	-0.79	*17%*	0.4	*67%*	0.66	*32%*
Dried mussel meat for chicken	-1.22	*12%*	-0.03	*84%*	0.24	*200%*
Fertilizer whole mussel	-0.98	*14%*	0.22	*267%*	0.48	*50%*
Chicken feed (cocked and dried, including shell)	-0.69	*19%*	0.51	*46%*	0.77	*26%*
Mussel shells (as chicken food additive)	-1.09	*13%*	0.1	*267%*	0.37	*76%*
Raw mussel meat (“BARF“)	-0.86	*16%*	0.09	*229%*	0.35	*84%*
Raw mussels unprocessed	-0.11	*59%*	0.51	*46%*	0.7	*30%*
Dog / cat food (recipe CAU)	-1.24	*11%*	-0.05	*76%*	0.22	*267%*

On the cost side, applying a social cost of carbon-style unit value to the combined climate footprint used here yields an indicative societal climate cost of approximately EUR 1 per kg fresh mussel (based on approximately 1.3 kg carbon dioxide equivalents per kg mussel and the unit value saying that corresponds to approximately EUR 0.99 per kg). This estimate is best interpreted as a value-chain externality associated with mussel farming and primary processing, rather than a net climate assessment. It does not include potential downstream substitution effects if mussel ingredients displace higher-impact proteins in pet food, nor does it quantify potential co-benefits linked to avoided waste treatment or alternative feed sourcing. While substitution effects could, in principle, change the sign and magnitude of net climate implications, the evidence base is currently too heterogeneous and assumption-sensitive to support robust monetised “climate benefit” claims for substitution in this report. A conservative interpretation is therefore warranted: decision-makers should assume that **farming and processing emissions constitute a real societal cost**, while **potential substitution benefits remain uncertain** and should not be relied on for quantitative claims without product- and market-specific modelling.

Overall, the synthesis supports the view emerging in the literature that **Baltic Sea mussel farming can deliver meaningful environmental benefits, particularly through nutrient extraction and related eutrophication mitigation, and that these benefits may be monetisable under certain governance and payment conditions**. The main remaining challenge for investment and scaling is therefore not the plausibility of environmental co-benefits per se, but the ability to achieve stable and investable profit margins across realistic product routes and scales. In this respect, the WP1 business planning work (especially D1.1) provides a valuable and promising foundation for identifying feasible value-chain configurations and bottlenecks that need to be resolved to translate sustainability potential into scalable commercial operations.

REFERENCES

Acuff, H. L., Dainton, A. N., Dhakal, J., Kiprotich, S., & Aldrich, G. (2021). Sustainability and Pet Food: Is There a Role for Veterinarians? [Review]. *Veterinary Clinics of North America - Small Animal Practice*, *51*(3), 563-581. https://doi.org/10.1016/j.cvsm.2021.01.010

Ahtiainen, H., Artell, J., Czajkowski, M., Hasler, B., Hasselström, L., Huhtala, A., Meyerhoff, J., Smart, J. C. R., Söderqvist, T., Alemu, M. H., Angeli, D., Dahlbo, K., Fleming-Lehtinen, V., Hyytiäinen, K., Karlõševa, A., Khaleeva, Y., Maar, M., Martinsen, L., Nõmmann, T., . . . Semeniene, D. (2014). Benefits of meeting nutrient reduction targets for the Baltic Sea – a contingent valuation study in the nine coastal states. *Journal of Environmental Economics and Policy*, *3*(3), 278-305. https://doi.org/10.1080/21606544.2014.901923

Ahtiainen, H., Lankia, T., Lehtonen, J., Lehtonen, O., Bertram, C., Meyerhoff, J., Pakalniete, K., Rehdanz, K., & Pouta, E. (2022). Welfare effect of substitute sites for coastal recreation – evidence from the Baltic Sea. *Journal of Environmental Economics and Policy*, *11*(4), 375-395. https://doi.org/10.1080/21606544.2022.2043188

AKTiiVS. (2022). *Socioeconomic assessment of marine ecosystem services. Report of the project "Improving*

knowledge on the state of the marine environment" (No 17-00-F06803-000001). https://www.varam.gov.lv/lv/media/32249/download.

Behaderovic, D., & Ziegler, F. (2020). *Miljöavtrycket av odlade blåmusslor jämfört med vanliga proteinkällor* (978-91-89167-81-0 (ISBN)). (RISE Rapport, Issue. http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-73779

Bertram, C., Ahtiainen, H., Meyerhoff, J., Pakalniete, K., Pouta, E., & Rehdanz, K. (2020). Contingent Behavior and Asymmetric Preferences for Baltic Sea Coastal Recreation. *Environmental and Resource Economics*, *75*(1), 49-78. https://doi.org/10.1007/s10640-019-00388-x

Biteau, C., Bry-Chevalier, T., Crummett, D., Loewy, K., Ryba, R., & St Jules, M. (2025). Have the environmental benefits of insect farming been overstated? A critical review [Article]. *Biological Reviews*. https://doi.org/10.1111/brv.70076

Brociek, R. A., & Gardner, D. S. (2025). Environmental impact of feeding plant-based vs. meat-based dry dog foods in the United Kingdom [Article]. *Frontiers in Sustainable Food Systems*, *9*, Article 1633312. https://doi.org/10.3389/fsufs.2025.1633312

Buer, A.-L., Maar, M., Nepf, M., Ritzenhofen, L., Dahlke, S., Friedland, R., Krost, P., Peine, F., & Schernewski, G. (2020). Potential and Feasibility of Mytilus spp. Farming Along a Salinity Gradient [Original Research]. *Frontiers in Marine Science*, *Volume 7 - 2020*. https://doi.org/10.3389/fmars.2020.00371

Centrum Balticum. (2018). *Speeding up the ecological recovery of the Baltic Sea*. https://www.centrumbalticum.org/files/3568/Speeding_up_the_ecological_recovery_of_the_Baltic_Sea.pdf

Costa, J. L. G., Bankuti, F. I., Oiko, O. T., Monti, M., Loureiro, B. A., Henríquez, L. B. F., Florindo, T. J., & Vasconcellos, R. S. (2024). Life cycle assessment of the production of an extruded dog food in Brazil [Article]. *Journal of Cleaner Production*, *458*, Article 142505. https://doi.org/10.1016/j.jclepro.2024.142505

Czajkowski, M., Ahtiainen, H., Artell, J., Budziński, W., Hasler, B., Hasselström, L., Meyerhoff, J., Nõmmann, T., Semeniene, D., & Söderqvist, T. (2015). Valuing the commons: An international study on the recreational benefits of the Baltic Sea. *Journal of environmental management*, *156*, 209-217.

European Commission. (2019). Commission Implementing Regulation (EU) 2019/627 of 15 March 2019 laying down uniform practical arrangements for the performance of official controls on products of animal origin intended for human consumption.

European Parliament and Council. (2004). *Regulation (EC) No 853/2004 of 29 April 2004 laying down specific hygiene rules for food of animal origin*.

Falconer, L., Cutajar, K., Krupandan, A., Capuzzo, E., Corner, R. A., Ellis, T., Jeffery, K., Mikkelsen, E., Moore, H., O'Beirn, F. X., O'Donohoe, P., Ruane, N. M., Shilland, R., Tett, P., & Telfer, T.

C. (2023). Planning and licensing for marine aquaculture. *Reviews in Aquaculture*, *15*(4), 1374-1404. https://doi.org/https://doi.org/10.1111/raq.12783

Filippelli, R., Termansen, M., Hasler, B., Timmermann, K., & Petersen, J. K. (2020). Cost-effectiveness of mussel farming as a water quality improvement measure: Agricultural, environmental and market drivers. *Water Resources and Economics*, *32*, 100168. https://doi.org/10.1016/j.wre.2020.100168

Frankignoulle, M., Pichon, M., & Gattuso, J.-P. (1995). Aquatic Calcification as a Source of Carbon Dioxide. In M. A. Beran, *Carbon Sequestration in the Biosphere* Berlin, Heidelberg.

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. *Nature*, *597*(7876), 360-365. https://doi.org/10.1038/s41586-021-03889-2

Gren, I.-M., Säll, S., Aklilu, A. Z., & Tirkaso, W. (2018). Does Mussel Farming Promote Cost Savings and Equity in Reaching Nutrient Targets for the Baltic Sea? *Water*, *10*(11), 1682. https://www.mdpi.com/2073-4441/10/11/1682

Hanley, N., Barbier, E. B., & Barbier, E. (2009). *Pricing nature: cost-benefit analysis and environmental policy*. Edward Elgar Publishing.

Hasselström, L., Thomas, J.-B. E., Nordström, J., Cervin, G., Nylund, G. M., Pavia, H., & Gröndahl, F. (2020). Socioeconomic prospects of a seaweed bioeconomy in Sweden. *Scientific Reports*, *10*(1), 1610. https://doi.org/10.1038/s41598-020-58389-6

Hautakangas, S., Ollikainen, M., Aarnos, K., & Rantanen, P. (2014). Nutrient Abatement Potential and Abatement Costs of Waste Water Treatment Plants in the Baltic Sea Region. *AMBIO*, *43*(3), 352-360. https://doi.org/10.1007/s13280-013-0435-1

Hedberg, N., Kautsky, N., Kumblad, L., & Wikström, S. (2018). Limitations of using blue mussel farms as a nutrient reduction measure in the Baltic Sea. *Report from Baltic Sea Centre*, *2*, 2018.

Hernández-Sancho, F., Molinos-Senante, M., & Sala-Garrido, R. (2010). Economic valuation of environmental benefits from wastewater treatment processes: An empirical approach for Spain. *Science of The Total Environment*, *408*(4), 953-957. https://doi.org/https://doi.org/10.1016/j.scitotenv.2009.10.028

Jarosch, L., Bach, V., & Finkbeiner, M. (2024). A life cycle assessment of vegan dog food [Article]. *Cleaner Environmental Systems*, *14*, Article 100216. https://doi.org/10.1016/j.cesys.2024.100216

Johnston, R. J., Rolfe, J., Rosenberger, R. S., & Brouwer, R. (2015). Benefit transfer of environmental and resource values. *The economics of non-market goods and resources*, *14*.

Jones, A. R., Alleway, H. K., McAfee, D., Reis-Santos, P., Theuerkauf, S. J., & Jones, R. C. (2022). Climate-Friendly Seafood: The Potential for Emissions Reduction and Carbon Capture in

Marine Aquaculture. *BioScience*, *72*(2), 123-143. https://doi.org/10.1093/biosci/biab126

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F. R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Jonsson, P. R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M. M., Mühl, M., . . . Virtanen, E. (2020). Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. *Science of The Total Environment*, *709*, 136144. https://doi.org/10.1016/j.scitotenv.2019.136144

Kuprijanov, I., Buhhalko, N., Eriksson, U., Sjöberg, V., Rotander, A., Kolesova, N., Lipp, M., Buschmann, F., Hashmi, A., Liblik, T., & Lehtonen, K. K. (2024). A case study on microlitter and chemical contaminants: Assessing biological effects in the southern coast of the Gulf of Finland (Baltic sea) using the mussel Mytilus trossulus as a bioindicator. *Marine Environmental Research*, *199*, 106628. https://doi.org/10.1016/j.marenvres.2024.106628

Langdal, A., Elvevoll, E. O., & Jensen, I.-J. (2025). Footprint cohesion and prevalence of environmental impact categories in blue mussel aquaculture life cycle assessments. *Cleaner Environmental Systems*, *18*, 100286. https://doi.org/10.1016/j.cesys.2025.100286

Maar, M., Larsen, J., & Schourup-Kristensen, V. (2023). Intensified Mussel Farming; Impacts on Nutrient Budgets and Ecology in a Eutrophic Semi-Enclosed Fjord System. *Journal of Geophysical Research: Biogeosciences*, *128*(2), e2022JG007312. https://doi.org/10.1029/2022JG007312

Mosna, D., Bottani, E., Vignali, G., & Montanari, R. (2021). Environmental benefits of pet food obtained as a result of the valorisation of meat fraction derived from packaged food waste [Article]. *Waste Management*, *125*, 132-144. https://doi.org/10.1016/j.wasman.2021.02.035

Nieminen, E., Ahtiainen, H., Lagerkvist, C.-J., & Oinonen, S. (2019). The economic benefits of achieving Good Environmental Status in the Finnish marine waters of the Baltic Sea. *Marine Policy*, *99*, 181-189. https://doi.org/https://doi.org/10.1016/j.marpol.2018.10.014

Olofsson, M., Karlsson, M., Melkersson, K., Minnhagen, S., Persson, M., Reutgard, M., Seehauser, M., & Muratovic, A. Z. (2025). Seasonal dynamics of biotoxins and potentially toxic phytoplankton in three Baltic Sea blue mussel farms. *Harmful Algae*, *147*, 102885. https://doi.org/10.1016/j.hal.2025.102885

Omstedt, A., Edman, M., Claremar, B., Frodin, P., Gustafsson, E., Humborg, C., Hägg, H., Mörth, M., Rutgersson, A., Schurgers, G., Smith, B., Wällstedt, T., & Yurova, A. (2012). Future changes in the Baltic Sea acid–base (pH) and oxygen balances. *Tellus B: Chemical and Physical Meteorology*, *64*(1), 19586. https://doi.org/10.3402/tellusb.v64i0.19586

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*(6392), 987-992. https://doi.org/10.1126/science.aaq0216

Risén, E., Nordström, J., Malmström, M. E., & Gröndahl, F. (2017). Non-market values of algae beach-cast management – Study site Trelleborg, Sweden. *Ocean & Coastal Management*, *140*, 59-67. https://doi.org/https://doi.org/10.1016/j.ocecoaman.2017.02.009

Ritchie, H., Rosado, P., & Roser, M. (2022). Environmental impacts of food production. *Our world in data*.

Sanders, T., Schmittmann, L., Nascimento-Schulze, J. C., & Melzner, F. (2018). High Calcification Costs Limit Mussel Growth at Low Salinity [Original Research]. *Frontiers in Marine Science*, *Volume 5 - 2018*. https://doi.org/10.3389/fmars.2018.00352

Sanders, T., Thomsen, J., Müller, J. D., Rehder, G., & Melzner, F. (2021). Decoupling salinity and carbonate chemistry: low calcium ion concentration rather than salinity limits calcification in Baltic Sea mussels. *Biogeosciences*, *18*(8), 2573-2590. https://doi.org/10.5194/bg-18-2573-2021

Saralegui-Díez, P., Villasante, S., Ospina-Álvarez, A., Ramón, M., & Moranta, J. (2026). The carbon footprint of the mussel food chain in Spain. *Resources, Conservation and Recycling*, *227*, 108742. https://doi.org/10.1016/j.resconrec.2025.108742

Söderqvist, T., Nathaniel, H., Franzén, D., Franzén, F., Hasselström, L., Gröndahl, F., Sinha, R., Stadmark, J., Strand, Å., Ingmansson, I., Lingegård, S., & Thomas, J.-B. (2022). Cost–benefit analysis of beach-cast harvest: Closing land-marine nutrient loops in the Baltic Sea region. *AMBIO*, *51*(5), 1302-1313. https://doi.org/10.1007/s13280-021-01641-8

Suckling, J., Druckman, A., Moore, C. D., & Driscoll, D. (2020). The environmental impact of rearing crickets for live pet food in the UK, and implications of a transition to a hybrid business model combining production for live pet food with production for human consumption [Article]. *International Journal of Life Cycle Assessment*, *25*(9), 1693-1709. https://doi.org/10.1007/s11367-020-01778-w

Sui, Y., Mohareb, E., Xue, L., Liu, G., & Smith, S. T. (2025). Mitigating environmental impacts of chicken production – The role of Co-product valorisation [Article]. *Journal of Cleaner Production*, *528*, Article 146750. https://doi.org/10.1016/j.jclepro.2025.146750

Thomsen, J., Ramesh, K., Sanders, T., Bleich, M., & Melzner, F. (2018). Calcification in a marginal sea – influence of seawater [Ca2+] and carbonate chemistry on bivalve shell formation. *Biogeosciences*, *15*(5), 1469-1482. https://doi.org/10.5194/bg-15-1469-2018

Timmermann, K., Maar, M., Bolding, K., Larsen, J., Nielsen, P., & Petersen, J. K. (2019). Mussel production as a nutrient mitigation tool for improving marine water quality. *Aquaculture Environment Interactions*, *11*, 191-204. https://www.int-res.com/abstracts/aei/v11/aei00306

Tyrrell, T., Schneider, B., Charalampopoulou, A., & Riebesell, U. (2008). Coccolithophores and calcite saturation state in the Baltic and Black Seas. *Biogeosciences*, *5*(2), 485-494. https://doi.org/10.5194/bg-5-485-2008

Vaher, A., Kotta, J., Stechele, B., Kaasik, A., Herkül, K., & Barboza, F. R. (2024). Modelling and mapping carbon capture potential of farmed blue mussels in the Baltic Sea region.

Science of The Total Environment, *947*, 174613. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.174613

Yavor, K. M., Lehmann, A., & Finkbeiner, M. (2020). Environmental impacts of a pet dog: An LCA case study [Article]. *Sustainability (Switzerland)*, *12*(8), Article 3394. https://doi.org/10.3390/SU12083394

Ziegler, F., Axelsson, A., Both, A., Filgueira, R., Strand, Å., Sundberg, H., Thomas, J.-B. E., Wocken, Y., & Tyedmers, P. (SUBMITTED). Blue mussels farmed across the northeast Atlantic using different technologies: Low-impact food despite inclusion of emissions from shell formation.

APPENDIX A: OVERVIEW OF PET FOOD-RELATED LCA LITERATURE

Study (author-year)	Geography / context	Product or system assessed	Main goal / question	Functional unit (FU)	System boundary (simplified)	Impact method (as reported)	Main hotspots / key findings
Yavor et al. (2020)	Generic "average dog" case (EU-oriented modelling)	Life cycle of a pet dog including diet and excreta	Quantify dog-related environmental impacts and identify dominant contributors	Average dog lifetime (dog system FU)	Full dog system incl. pet food + urine/feces (use-phase emissions included)	Multiple categories (reported as 15 categories)	Pet food dominates most categories; freshwater eutrophication largely driven by urine/feces; feces important for freshwater ecotoxicity; boundary choice changes mitigation levers
Suckling & Druckman (2020)	UK	Cricket rearing for live pet food	Identify impacts and hotspots of UK cricket production; explore improvement options	Case-business output (study-specific; live crickets)	Cradle-to-farm-gate (attributional)	ILCD 2011 Midpoint+	Energy demand (especially heating) and feed inputs are key drivers; impacts higher than warm-climate comparators; efficiency and hybrid market model can improve performance
Mosna et al. (2021)	Italy / EU supply chain	Wet pet food using "meat fraction" recovered from packaged food waste	Test whether valorisation into pet food reduces impacts vs baseline disposal + conventional ingredients	1 kg pet food	Scenario comparison covering waste treatment + ingredient substitution and pet food production	ReCiPe 2016	Meat production dominates GWP/land use in baseline for some products; packaging can dominate GWP for certain wet formats; benefits depend on baseline disposal and displaced ingredients
Costa et al. (2024)	Brazil	Extruded dry dog food (premium)	Quantify cradle-to-gate impacts and identify hotspots for eco-design	2.59 MJ/day feeding requirement (10 kg dog); reference flow ~177.3 g/day	Cradle-to-gate including raw materials, manufacturing, and distribution (as modelled)	Environmental Footprint (EF 3.0)	Formulation contributes ~70–90% of impacts; key categories include eutrophication, acidification, particulate matter, climate change; ingredient selection is the main lever

Brociek & Gardner (2025)	UK retail market	31 commercial dry dog foods (plant-based, poultry, beef/lamb, veterinary diets)	Compare footprints across diet types/protein sources	Per 1,000 kcal fed	Product/ingredient modelling (retail products; study-specific modelling boundary)	Ingredient-based footprinting approach (study-specific)	Strong gradient by protein source: plant-based lowest, poultry intermediate, beef/lamb highest across indicators; supports protein-type hotspot narrative
Jarosch et al. (2024)	Germany	Commercial canned wet vegan dog food	Identify hotspots of vegan wet dog food; improve comparability via PEFCR alignment	419 kcal prepared wet food in packaging (PEFCR-aligned FU)	Ingredients + packaging + distribution + use (dishwashing) + end-of-life (full product life cycle)	PEFCR/PEF-aligned (selected categories reported)	Packaging and downstream stages can remain relevant hotspots for wet formats; demonstrates trade-offs even when livestock ingredients are excluded
Sui et al. (2025)	UK	Chicken co-product treatment pathways (pet food, rendering, incineration, anaerobic digestion)	Compare treatment/valorisation routes; test allocation and system expansion sensitivity	Scenario-based tonnage flows (study-specific)	Includes breeding/slaughter/ transport/processing + alternative disposal/valorisation routes; sensitivity on system expansion	Multi-category assessment (method reported in paper; emphasis on scenario comparison)	"All co-products to pet food" scenario lowest among tested; incineration highest; results highly sensitive to avoided products under system expansion and to allocation choice (economic vs mass)
Biteau et al. (2025)	Multi-study review	Insect farming environmental performance (food/feed incl. pet food relevance)	Critically assess whether benefits are overstated; identify key uncertainties	Not applicable (review)	Not applicable	Not applicable	Benefits often context-dependent; many LCAs small-scale; constraints on "waste-fed" assumptions and frass utilisation; when fed feed-grade inputs and used as feed, insects may add burdens depending on substitution
Acuff & Aldrich (2021)	Conceptual / veterinary practice	Pet food sustainability framing and role of veterinarians	Synthesise key concerns and actionable levers; interpret LCA for practice	Not applicable (conceptual/review)	Not applicable	Not applicable	Highlights multi-dimensional sustainability (ingredients, manufacturing, packaging, transport, waste); stresses careful interpretation of LCA choices and nutritional adequacy constraints

APPENDIX B: OVERVIEW OF ECOSYSTEM SERVICES FROM BALTIC MUSSEL FARMING

Ecosystem service or effect	Baltic Sea (brackish)	Non-brackish (marine/freshwater)	Baltic-specific notes
Nutrient removal (N, P)	High potential, but strongly context-dependent	High; often higher per unit area/time in marine settings	Lower efficiency in low salinity (slower growth, lower nutrient content); higher potential toward more saline sub-basins
Water purification / water clarity	Significant; can improve transparency	Significant; often more robust in high-salinity marine systems	More variable across sites; outcomes depend on hydrodynamics, background productivity, and farm scale
Habitat provision / local biodiversity support	Can support macrophytes and local fauna via added structure	Often supports diverse benthic/pelagic communities around farm structures	Similar mechanisms, but communities typically less diverse; effects are site- and intensity-dependent
Food provisioning	Limited (low growth, small size)	Major provisioning service (food markets) in many regions	Often framed primarily as mitigation farming; food markets typically secondary without specific niches/valorisation routes
Economic viability	Low without subsidies and/or integration (e.g., IMTA)	Generally higher, especially where food markets and established value chains exist	Frequently assessed as cost-effective for nutrient abatement under supportive policy/payment schemes; profitability for food alone is challenging
Cultural / social value	Local identity and recreation benefits, but less documented/quantified	Often stronger where aquaculture traditions are longstanding (e.g., Mediterranean)	Literature emphasis is commonly on remediation; social acceptance and perception can be barriers and require engagement
Contaminant monitoring (bioindicator role)	Effective, but higher physiological stress/uptake may occur	Effective; often lower physiological stress relative to brackish constraints	Sensitivity and bioaccumulation patterns can differ; site selection near pollution sources is critical for food/feed uses
Risk / disservice: local hypoxia	Present if poorly managed or in low-flushing sites	Present, but can be less pronounced depending on flushing and background oxygen conditions	Baltic susceptibility can be higher due to stratification and oxygen sensitivity; requires careful siting, density control, and monitoring

APPENDIX C: BALTIC ECOSYSTEM SERVICE VALUES

Study	Ecosystem service valued	Value	Unit	Valorisation method	Key details (scope/location)
Ahtiainen et al. (2022)	Coastal/marine recreation linked to environmental quality (consumer surplus)	66.9–83.3	EUR per visit	Travel cost method (consumer surplus)	Estimated CS/visit for Germany (83.3), Finland (79.5), Latvia (66.9); used for benefit-transfer/scaling (in Pakalniete et al. 2023)
Ahtiainen et al. (2022)	Coastal/marine recreation (consumer surplus)	176–604	EUR per person per year	Travel cost + scaling using trip rates	Derived from CS/visit combined with trip frequency assumptions in the Annex (Germany 176; Finland 604; Latvia 254). (in Pakalniete et al. 2023)
Bertram et al. (2020)	Regional recreation benefits under improved water-quality scenario	~9.5	billion EUR per year	Contingent behaviour + scaling with CS estimates	Annex uses contingent behaviour (trip changes under scenarios) to scale regional recreation benefits for a "best case" scenario vs current.
Ahtiainen et al. (2014)	Non-market welfare benefits of reducing eutrophication (BSAP targets)	3,603	million EUR per year	Contingent valuation (WTP)	Total WTP across nine Baltic littoral countries to reach eutrophication objectives (in Pakalniete et al. 2023)
Czajkowski et al. (2015)	Recreation welfare benefits of improved Baltic Sea status	1,969	million EUR per year	Travel cost method (recreation demand; CS change)	Change in total consumer surplus for improved status vs current; Baltic-wide. (in Pakalniete et al. 2023)
Nieminen et al. (2019)	Welfare benefits of achieving Good Environmental Status (GES)	~470.5	million EUR per year	Contingent valuation (WTP)	Aggregate Finnish household WTP (as summarised in the attached material). (in Pakalniete et al. 2023)
Östberg et al. (2012)	Local coastal water-quality improvement benefits	6.4	million EUR per year	Local valuation of water-quality improvement (as used in CBA materials)	Swedish coastal case (Himmerfjärden/Stockholm archipelago context in the supplementary material).
Risén et al. (2017)	Cultural/amenity value of improved beaches	28–54	EUR per person per year	Stated preference (WTP)	WTP for two beach enhancement programmes (A/B), used in beach-related CBA contexts. (in Pakalniete et al. 2023)

Co-funded by the European Union

APPENDIX D: NUTRIENT REGULATION VALUES

Study	Ecosystem service valued	Value	Unit	Valorisation method	Key details (scope/location)
Hautakangas et al. (2014)	Nutrient regulation (N and P abatement cost proxy)	4.3–4.7 (N); 13.6–15.2 (P)	EUR per kg N; EUR per kg P	Abatement cost (WWTP)	Costs depend on abatement level and WWTP size; used as unit-cost benchmarks Pakalniete et al (2023).
Hernández-Sancho et al. (2010)	Nutrient regulation (shadow values)	4.6–65.2 (N); 7.5–103.4 (P)	EUR per kg N; EUR per kg P	Shadow price from WWTP cost structures	Implied pollutant "prices" inferred from treatment cost structures; ranges reflect assumptions. (Pakalniete et al 2023)
Hasselström et al. (2020)	Eutrophication mitigation (unit benefit values)	7.6 (N); 86.5 (P)	EUR per kg N reduced; EUR per kg P reduced	Synthesis/derivation (as reported in CBA supplementary)	Unit benefit values reported in supplementary material (not re-derived here).
AKTiiVS (2022)	Nutrient regulation (abatement cost benchmark)	16	EUR per kg (nutrient)	Observed/derived abatement-cost benchmark	Based on Latvian tertiary treatment plant data (2018), reported second-hand in Pakalniete et al (2023)
Centrum Balticum (2018)	Nutrient regulation (abatement benchmark)	19 (N); 86 (P)	EUR per kg N; EUR per kg P	Abatement-cost/value benchmark	Benchmark values reported in Pakalniete et al (2023); underlying method details in the original Centrum Balticum publication.