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Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
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Thomas Robert Malthus :

“The world's population will multiply more rapidly than the available food supply”

Preface and Acknowledgement

This doctoral thesis is submitted to the Department of Biotechnology and Food Science, the faculty of Natural Science at the Norwegian university of science and technology (NTNU). as a partial fulfillment of the requirements for the degree of Phelosophiae Doctor.

This research targets the efficient utilization of the rest raw materials of the Norwegian farmed salmon value chain. The research was part of the OPTIMAT research project (a comprehensive research project dealing with marine food resources).

My educational background is B.Sc. in food science and human nutrition , M.Sc. in Agriculture and biotechnology for arid-land sustainable development. I worked for many years in the food industry for several companies in different countries around the world. Part of my work experience was seafood industry in Alaska-USA, in wild salmon processing, where I had my first experience with the handling of the salmon rest raw material. And during my research I had the opportunity to visit salmon processing factories in Norway and Faroe Islands.

I always wanted to do research work that could contribute to the collective knowledge about sustainable food production. I placed my research questions, findings, with my experiences and accumulated knowledge in this thesis and I sincerely hope for those who will read it that they gain benefit from it.

My sincere gratitude to all my teachers who created my entire learning journey starting from the alphabets all the way to the PhD. My deep appreciation and gratitude to My supervisor Associate professor Eirin Skjøndal Bar for her guidance, valuable advice, and mentorship. I am very thankful to Professor Turid Rustad for co-supervising this research project and giving me great advice that helped me a lot. Special thanks to Professor Eva Falch for giving me the great opportunity to do my teaching duties in her courses. My deep appreciation and sincere gratitude to the Norwegian University of Science and Technology NTNU .

Mohd H.M. Abualtaher

Trondheim, June 23rd 2022

Abstract

The necessity for transformation of the food systems toward sustainability is a point of scientific consensus. At the core of the quested transformation falls the concept of optimizing biomass utilization efficiency. There is a global need for more food, to meet the nutritional needs of a steadily growing population and to counter global environmental challenges. Norwegian salmon farming is a globally significant seafood production system; imports raw material for salmon feed from multiple countries and exports the salmon product to more than 80 countries. Post-harvest processing of the salmon results in huge quantities of rest raw material. The main aim of this thesis is to define a scheme for optimum utilization of salmon rest raw material within the human food system. To achieve this target, this thesis develops and applies a novel interdisciplinary approach, that combines systems engineering, material flow analysis and the Sustainable development goals (SDGs) framework. This approach resulted in four papers where each one of them provided insight on a concept of systemic transition to sustainable rest raw material usage. Paper I provides an understanding for the role of material flow analysis studies in developing a sustainable salmon value chain, describing, and validating the relation between material management and sustainability. Paper II explores salmon production system structure and decision-making dynamics in relation to the post-harvest processing byproducts usage. Redefining the salmon rest raw material as industrial food-loss creates the connection with the food-loss reduction target in UN SDGs framework. Moreover, system's performance and practices were studied under the shadows of sustainability and food security. Paper III came up with a novel method for food-loss assessment at operational level, through a systemic protein inventory for the Norwegian salmon value chain starting from the input of raw material as salmon-feed to the output of salmon products and rest raw material. Paper IV focused on verifying the systemic integration of the UN sustainable development goals within the Norwegian salmon value chain. This integration gives credibility to the proposition of SDGs as the sustainability context for system's development. This research reveals the embodied motives within the Norwegian salmon value chain to develop measures for food-loss reduction.
The papers established an understanding for salmon rest raw material utilization as an industrial food-loss, introduced a customized method for its assessment and anchored it with the sustainable development goals framework that the system is committed-to .

Abbreviations:

CDA	Critical discourse analysis
CE	Circular economy
FAO	Food and agriculture organization
FL	Food loss
FLI	Food loss index
FW	Food waste
KPI	Key performance indicator
MFA	Material flow analysis
NGO	Non-governmental organizations
NSVC	Norwegian salmon value chain
RQ	Research question
RRW	Rest raw material
SE	Systems engineering
SDG	Sustainable development goals
SFA	Substance flow analysis
UN	United nations
UNICEF	United nations international children's emergency fund

Contents

Papers in appendix

Paper I :

Review of applying material flow analysis-based studies for a sustainable Norwegian Salmon aquaculture industry.

Journal of Applied Aquaculture. 2020; 32:1,1-15 https://doi.org/10.1080/10454438.2019.1670769

Paper II :

Systems Engineering Approach to Food Loss Reduction in Norwegian Farmed Salmon Post-Harvest Processing.

Systems. 2020; 8(1):4, https://doi.org/10.3390/systems8010004

Paper III :

Food-Loss Control at the Macronutrient Level: Protein Inventory for the Norwegian Farmed Salmon Production System.

Foods 2020, *9*, 1095. https://doi.org/10.3390/foods9081095

Paper IV :

Systemic Insights on integration of UN sustainable development goals within the Norwegian salmon value chain.

Applied Sciences 2021; 11(24):12042. https://doi.org/10.3390/app112412042

Contributions to papers

I have initiated and led papers I, II, III and IV. Being the lead author, I wrote the manuscripts, and submitted them to the journals. I conceptualized, structured, and wrote the four papers. My supervisor Associate professor Eirin Bar edited the manuscripts, gave advice and guidance on the research. Professor Rustad was a second author in paper IV she contributed to the discussion with valid reflections on the Norwegian salmon industry and edited the manuscript before submission.

1.0 Introduction

1.1 Norwegian farmed salmon and rest raw material:

Norwegian salmon aquaculture is a global seafood provider with proven capacity to embrace sustainability[1]. The Norwegian seafood industry is export oriented, with more than 90% of production being exported to other countries[2]. It is economically significant, generates great revenue, employ thousands and has been steadily growing since its beginning in the 1970s[3, 4]. The salmon is farmed in sea cages placed in open marine environment. Atlantic salmon farming is a large and growing industry in Norway with an annual production of about 1.3 million tons[4]. In 2019 Norway produced 1 364 044 tons of Salmon in 1369 sites[5]. Post-harvest processing of the salmon produces rest raw material (RRM) beside the main product, the salmon fillet. The term "RRM" is frequently used to describe the "byproduct" or "co-product" in both industrial and scientific terms. The Norwegian national regulations define "by-products" as products not intended for human consumption while "co-products" are for human consumption[6]. However, as long as the rest raw materials are treated and processed in a proper way and according to the regulations, the final products are well suited and potentially applicable for both animal and human consumption[7]. The term by-product is also used as part of the term "byproduct management activities" including the material sorting and grading[8]. In general, the by-products from fish industry can account for up to 75% of the catch including the postharvest processes[9]. Post-harvest fish losses are a major concern in fish value chains all over the world, because it is a loss of income and it contribute to food insecurity[10]. The salmon RRM consists of viscera, heads, frames, skin, blood and trimmings ; about 336 000 tons wet weight are annually available for further processing[11]. From the amount of available RRM that arises in the Norwegian salmon value chain (NSVC); it is estimated that 89 % is utilized, split into different feed ingredients (87%), and a small part as biogas/energy [11]. Traditionally about 50% of the Atlantic salmon RRM in Norway are minced and acidified to produce semi fluid material called silage used mainly as a raw material in animal feed production[11]. Acidified hydrolysis combined with heat treatment decreases the nutritional value of salmon RRM, breaking down protein into less value nitrogenous compounds[12]. The quality of the RRM at the processing site is the limiting factor in its manufacturing possibilities, fish rest raw material could easily be ruined by microbial spoilage, enzymatic reactions and oxidation if not preserved properly or processed quickly[13, 14]. The salmon aquaculture production sector in Norway is regulated to aim at profitability, competitiveness and sustainable development (Aquaculture-Act 2005)[15].. The Norwegian salmon production system operates within a declared sociopolitical context of care and demand for sustainable production[16, 17]. The Norwegian policies with commitment to sustainability including the global Agenda 2030 framework, creates influential context for the development of a sustainable seafood production system[18]. There is a scientific consensus that salmon RRM are rich source of nutrients[19-22]. Salmon RRM have economical potential and market value. Moreover, there is a growing research trend to optimize their utilization. Research on salmon RRM so far mainly aimed for extracting high-quality ingredients for industrial applications[9, 12, 23-28]. However, classifying salmon rest raw material as food-loss and the usage of their entire bulk to be turned to a food product is not taking a big part of the common discussion yet. Efficient utilization of salmon rest raw material within the human food system can add between 290-400 kilotons/year of affordable food and nutrients to the global food table[29].

1.2 Food security for a global population

Food security occurs when all people at all times have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (World Food Summit, 1996). Global status of food security means that every human has steady access to a diet that contains enough protein, calories and all the essential micronutrients. Efficient and sustainable food production systems are expected to create that availability of food and nutrients. UN agenda 2030 and the Sustainable development goals have been focused on the development of responsible food production and consumption systems. More particularly food-loss and food waste reduction among all other aspects of efficient utilization of natural resources and minimizing the associated environmental impacts.
Thomas Robert Malthus; 18th century economist and demographer who stated that human population growth is exponential, while the progression of food production growth is much lower, resulting unavoidable food scarcity that could jeopardize the survival of humankind[30]. Planet earth has finite natural resources, it is stressed to provide for exponentially growing human population[31], a concern that is attributed to Malthus and commonly shared by sustainability researchers as the Malthusian dilemma.

The world population of 7.7 billion in 2019 is expected to reach 9.7 billion in 2050 [United Nations, Population Division (2019)]. FAO report in 2020 on the state of food security in the world clearly state that 12 percent of the global population was severely food insecure, representing 928 million people – 148 million more than in 2019. Food insecurity is caused by climate variability, economic hardships, poverty, famines, and conflicts[32-36]. During this research project the world experienced the COVID 19 pandemic and the war in Ukraine; both crises severely affected the global food supply chains[37, 38]. The COVID19 pandemic was estimated to push up to 132 million people into hunger by the end of 2020, according to a report from the United Nations. UNICEF stated in July 2020 that "As progress in fighting hunger stalls, the COVID-19 pandemic is intensifying the vulnerabilities and inadequacies of global food systems - understood as all the activities and processes affecting the production, distribution and consumption of food". Ukraine is major food producer: It accounts for about 17% of global corn exports, 12% of wheat, 30% of world sunflower seeds and significant quantities of barley and rapeseed. The war is a major disturb for the global food supply chains and the global food market balance. The shadows of a global food crisis are now more present in the world's consciousness. Threats to food security for a growing population are not limited to total current food production, but also how it is distributed, including the dominance of unsustainable industrial production and wasteful consumption practices and behavior[39]. The world needs more food and that drives seeking more efficient food systems with minimum food-loss.

1.3 Food systems transformation

The urgency of food system transformation is now irrefutable[40]. The global challenges of global food security, malnutrition , climate change , water scarcity, pandemic COVID-19 and military conflicts are all reasons for accelerating this transformation. Food systems resilience, productivity, environmental impacts reduction and natural resources efficient usage are the main principles to reform and develop the way food is being produced, delivered, and consumed. Aligning food systems transformational process with the UN Agenda 2030, sociocultural approach and inclusiveness of stakeholders role are foundational elements in the transformation strategies and developing sustainable practices[41]. The global food system need to be more resilient and more sustainable[42]. Food systems need to be transformed to be more productive, more inclusive of poor and marginalized populations, environmentally sustainable while capable to deliver healthy and nutritious diets to all. These are complex and systemic challenges that require the combination of interconnected actions at the local, national, regional, and global levels. The global challenges of hunger and malnutrition and potential solutions all have direct organic relation with food production systems. FAO estimated that around 1/3 of the world's food is lost or wasted every year[43-45]. The food produced globally is wasted along the food chain, representing a burden for the environment and an inefficiency of the food system[46]. Food loss and waste (FLW) are associated with about one-quarter of land, water, fertilizer used for crop production[47] and 10% of the global green-house emissions[48]. There is a global perception of the problems of food waste and food loss as issues of great public concern. Decreasing food loss and waste through more efficient systems is perceived as a key element in solving world's food challenges[49]. The 2030 Agenda for Sustainable Development reflects the increased global awareness of the food-loss\waste problem and the serious intention to create solutions for it.

Food system (FS) is a concept that encompass the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal of food products that originate from agriculture, aquaculture, forestry or fisheries, and parts of the broader economic, societal, and natural environments in which they are embedded[50]. The food system is composed of sub-systems (e.g., farming system, waste management system, input supply system, etc.) and interacts with other key systems (e.g., energy system, trade system, health system, etc.). Therefore, a structural change in the food system might originate from a change in another system; for example, a policy promoting more biofuel in the energy system will have a significant impact on the food system[50]. A sustainable food system is a food system that delivers food security and nutrition for all without compromising t the economic, social, and environmental bases to generate food security and nutrition for future generations. This means it considers and include the three pillars of sustainability: economy, society and environment [50-52]. A sustainable food system lies at the heart of the United Nations' Sustainable Development Goals (SDGs)[53]. Globally adopted in 2015, the SDGs call for major transformations in agriculture and food systems to end hunger, achieve food security and improve nutrition by 2030[54]. Food security is related to all the United Nations Sustainable Development Goals (SDGs). More in particular, SDG 2 "zero hunger", SDG 12 "responsible consumption and production"; and SDG 12.3 halve per capita global food waste/food loss along production and supply chains, including post-harvest losses[55].

Industrial food-loss: Food-Loss refers to food that gets spilled, spoilt, or otherwise lost, or incurs reduction of quality and value during its process in the food supply chain before it reaches its final product stage. Food loss typically takes place at production, post-harvest, processing, and distribution stages in the food supply chain. Food-loss is the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retailers, food service providers and consumers. Empirically, it refers to any food that is discarded, incinerated, or otherwise disposed of along the food supply chain from harvest/slaughter/catch up to, but excluding, the retail level (food-waste), and does not re-enter in any other productive utilization. Food loss, as reported by FAO in the food-loss index (FLI), it occurs from post-harvest up to, but not including the retail and consumption level where it is described as food-waste (FW). Sustainable operations; where food-loss is mapped for each processing stage, plays a significant role in food-loss reduction[56]. **The SDGs framework** mentioned FL clearly under goal 12, which refers to 'Responsible Production and Consumption', the concept of food loss and waste (FLW) management through target **12.3**: 'By 2030, halve per capita global Food Waste at the retail and consumer levels and reduce Food Losses along production and supply chains, including post-harvest losses[57, 58].

Food-loss assessment and reduction: food-loss can reach up to 48% of the total calories being produced by a food value chain. avoiding food-loss requires solutions to be developed by all the involved actors [59]. The primary causes for food-loss are logistical, technological, inadequate practices, and poor management [60]; with considerable variations between different production systems in different countries. Food-loss reduction requires a systemic paradigm shift, changing attitudes, practices, technologies, and developing strategic policies. For that to be reached; influence on decisions makers need to be made. There are multiple aspects and levels of involvement in the food-loss challenge, industrial, commercial, social and institutional. Any solution will not only concern all the involved in processing, preparing, preserving, distributing, and serving or selling food products but also the governmental agencies with responsibilities related to food, environment, agriculture, public health, and social development. The social sector, the nongovernmental organizations (NGOs) and scientific researchers are involved in working on reducing food-loss and food waste; all considered stakeholders in this issue [61]. Post-harvest food-loss reduction was found to have impacts on the economic development and social welfare both locally and globally. Moreover, the challenges of food security, economic revenues, employment in the food sector, and environmental impacts are very relevant to the food-loss problem. Following a holistic approach that involves all the elements gives strength to the management and motivation to mobilize resources to target the food-loss reduction [62].
In conclusion, the food-loss reduction challenge expands vertically from local, regional, national, up until global levels and horizontally over multiple sectors, institutions, and stakeholders[63]. The size of the FL problem was proven severe and its reduction must be pursued [64]. The nature of the FL problem is systemic consecutively, developing a solution for it will rise from analyzing its systemic causes [65]. Material flow management is central in the food-loss problem and the targeted reduction is all about the most efficient usage of that material within the human food system[66].

1.4 Sustainability

The concept of sustainability evolved through times, starting from the Brundtland report that states: Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs[67]. Sustainability is a collective term that describes a continuingly powerful and influential meeting point of ideas and politics[68]. The challenge of sustainability has multi-dimensional nature; technical and rational, it is more of a change in attitude and behavior. Sustainability therefore must include the social discourse where the fundamental issues are explored collaboratively within the concerned groups or communities. Sustainability usually confront and challenge the dominant paradigms that are seen as desirable[69]. A social definition of sustainability might include the continued satisfaction of basic human needs like food, water, and shelter as well as higher level needs; social and cultural such as security, freedom, education, employment, and recreation as suggested by Maslow's hierarchy of needs[70]. The concepts of Circular Economy (CE) and sustainability are both increasingly gaining traction with academia, industry, and policymakers, with similarities and differences between both concepts that remain vague[71]. The concept of CE is based on strategies, practices, policies, and technologies to achieve principles related to reusing, recycling, redesigning, repurposing, remanufacturing, refurbishing, and recovering water, waste materials, and nutrients to preserve natural resources[72]. It provides the necessary conditions to encourage economic and social actors to adopt strategies toward sustainability. However, the increasing complexity of sustainability aspects means that traditional engineering and management/economics alone cannot face the new challenges and reach the appropriate solutions[72]. The environmental threats, social development demands (worker rights, consumer's awareness) and economic growth needs (market and nonmarket goods and services, global competitiveness) are forcing all stakeholders along the supply chain of seafood and aquaculture sectors to achieve the transition to sustainability and circular economy[73]. CE practices are not only relevant to SDGs but also aidful for their implementation[74]. The global seek for sustainable development materialized in the UN Agenda 2030 and the SDGs framework that included all the defined aspects of sustainability. The SDGs create a scientifically robust framework for fairness and sustainability at every level: from planetary biosphere to local communities; aiming to end poverty, protect the planet and ensure that all people have peace and prosperity, now and in the future[75]. The concept of circular economy is more related in terms of reduction, reuse, and recycling than the idea of a systematic change in the food supply chain. Moreover, associating food losses and wastes with the circular economy remains a global challenge that needs future research to develop applicable solutions [76]. The global action agenda to achieve the Paris Agreement on climate change and sustainably feeding the planet by 2050 include reducing food loss and waste as SDG Target 12.3 clearly stated[77].

2.0 Theoretical structure of the thesis

The global demand for more food and nutrients is increasing and expected to increase more in near future[78-81]. The main objective of this study is to define a scheme for optimum utilization of salmon rest raw material within the human food system. Could that be addressed as part of the system's transition to sustainability and its sustainable development endeavor?

Material

Salmon rest raw material is a substantial fraction of a harvested biomass that is grown in a resource-costly process[82, 83]. The salmon farming process metabolizes raw material as feed to produce a marketable food product (goods) and secondary byproduct (rest raw material) that goes for non-food uses despite its content from nutrients and freedom from hazards. This thesis reidentified the rest raw material as food-loss, due to its significant content of nutrients, the significant amounts of nutrients invested in growing the salmon, and its current final usages outside the human food system (see figure 1). This is explained in detail in papers II & III.

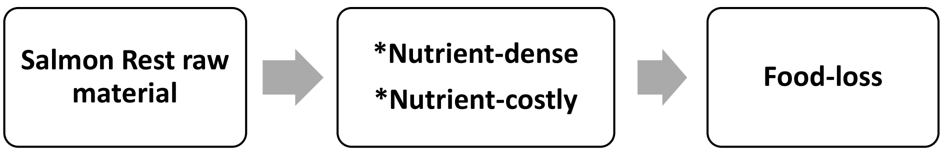

Figure 1 Rest raw material redefined as food-loss.

System

Salmon farming is composed of multi-stage consecutive processes and group of activities synchronized to achieve an objective target; It is a system. A System is a construct or collection of different elements that together produce results not obtainable by the elements alone as defined by the International Council on Systems Engineering (INCOSE). Moreover, in business terms it can be described as a value chain. A value chain is a concept describing the full chain of a business's activities in the creation of a product or service, from the initial reception of materials all the way through its delivery to market, and everything in between[84]. The system is directed, governed, and controlled by its decision makers, who are influenced by system's stakeholders. Behind the system there is a pool of knowledge and information that system's decision makers and stakeholders rely on[85]. (See figure 2). The systemic approach was considered in all the four papers. Systems engineering principles, were deployed to develop insight into the salmon post-harvest processing system's behavioral dynamics that are causing FL and to identify the necessary concepts to create solutions. FL problem must be addressed through the systemic behavior of downgrading the RRM to non-food uses as major cause[85].

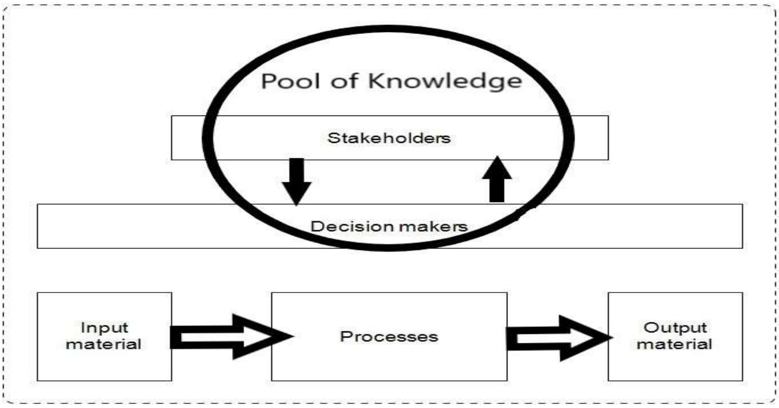

Figure 2 NSVC System structure and internal interaction.

Sustainability

The Salmon farming system in Norway operates within a socio-political background of commitment to sustainability[17]. Care for sustainable production falls in the main scope of the NSVC system and appears in its environmental practices[16, 86]. While there are different sustainability narratives and strategies[87], the United Nations sustainable development goals SDGs framework is very holistic, inclusive of all aspects of sustainable development, sets clear targets. The NSVC is committed to SDGs achievement[88] as this thesis verified in paper IV. The SDGs framework include the food-loss reduction as global target (see figure 3). The SDGs definition of food-loss was adopted by this thesis in papers II and III as a main concept.

Figure 3 SDGs & Food-loss reduction target.

The three main theoretical abstractions: Material, System and Sustainability were localized on the research case study and formulated the hypothesis. The rest raw material as food-loss, the System is the NSVC and Sustainability as the integration of the SDGs framework (see figure 4)

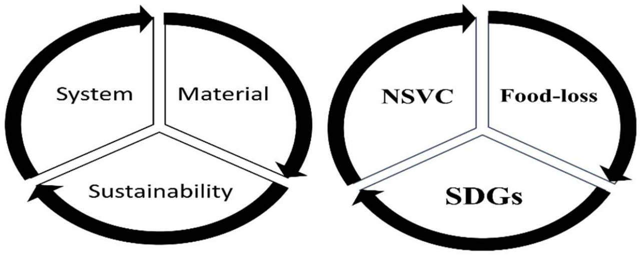

Figure 4 Reflection of the main theoretical concepts of this thesis

This study hypothesizes that: Anchoring the salmon RRM utilization challenge with NSVC system's sustainable development endeavor can be achieved through properly re-identifying this material as food-loss. If this linkage is well established, Salmon RRM will take the necessary attention, stimulate embodied motives, and receive efforts toward their development for food usage.

Based on this overall aim the specific research questions were:

RQ 1. How does the material flow relate to NSVC system's sustainability ?

RQ 2. Is salmon RRM a systemic industrial food-loss ?

RQ 3. How can food-loss in the Norwegian salmon industry be estimated ?

RQ 4. Do sustainable development goals create context to the NSVC system's reformation ?

To define an answer for the research questions they were allocated to the relevant discipline of knowledge, methods and frameworks as summarized in **(Table 1).**

Table 1 : Theoretical multi-disciplinary structure

Theoretical Elements	Discipline of knowledge	Applied in thesis	Paper
Material	Material flow analysis	Material & sustainability Method for Food loss assessment	I III
System	Systems engineering	Gain insight on the system Systemic Paradigm shift	II, IV II
Sustainability context	Sustainable development Goals	SDG 12.3.1 food loss reduction Verify SDGs systemic integration	II, III IV

The four published papers are presenting coherent knowledge and understanding that contributes to the thesis. Each paper designed to serve a task to answer a research question, investigate and establish a concept obtained from the thesis hypothesis (Figure 5).

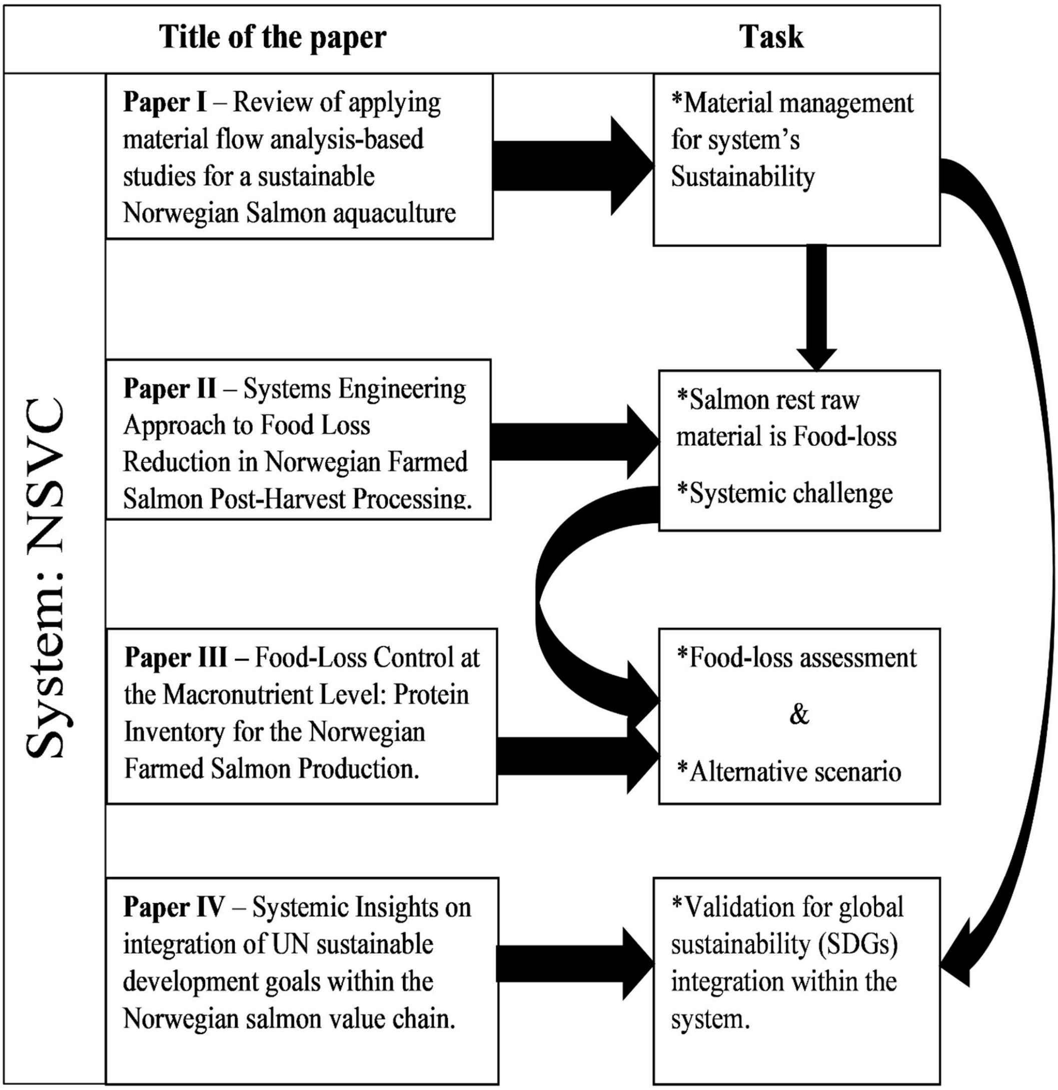

Figure 5 Papers and the research tasks.

3.0 Research approach and Methodology

This research combines multiple methods to identify key drivers that cannot be easily quantified. The start point observation is the significant amounts of salmon RRM that are being produced by NSVC annually and the growing interest in optimizing their utilization. The seek for efficient utilization of salmon RRM was approached in this thesis as a challenge to NSVC sustainability. This narrative requires exploring the system and material in a sustainability context, aiming to conceptualize the findings and conclusions as a research answer to the primary observation. This inductive approach to obtain verified knowledge is structured on three pillars: Systems engineering, Material flow analysis and recognizing the Sustainability context.

The methodological approach that this thesis followed is three-fold. Methods for knowledge obtainment, methods for system's understanding, and methods for quantified modeling with scenario creation, as summarized in table 2.

Table 2 Summary of methods in relation to theoretical approach.

Theoretical approach	Method
Knowledge acquisition	Systemic literature review UN SDG framework Critical discourse analysis **CDA**.
System's understanding	Systems engineering **SE**, Systems thinking.
Quantified modeling, Scenario creation	Material Flow Analysis **MFA**

*Information and Data acquisition relied on Data banks, per revised publications, corporate reports, governmental white documents, governmental statistics, official reports, and experts opinions as sources.

In paper I, A Systemic review of previously conducted material flow analysis MFA studies on the Norwegian farmed salmon and their sustainability related findings. In paper II systems engineering principles were applied to address the research problem of salmon RRM as a food loss to understand it and analyze its causes. The 3rd paper MFA method was applied for quantitative support of the findings from paper II and develop a data supported alternative scenario. In paper IV SE principles were applied then followed by critical discourse analysis to develop a framework to clarify and prove the presence of SDGs as sustainability guiding narrative adopted by the system and creates context to its reformation. All Methods mutually served and supported each other in making the whole picture clearer. The usage of food-loss terms and definitions obtained from SDGs to address the RRM challenge was applied in papers II & III.

3.1 Material flow analysis (MFA) : MFA is a family of methods including substance flow analysis (SFA), Nutrient flow analysis (NFA) and life cycle assessment (LCA) according to the traced material, substance, or nutrient and the application of the method[89]. MFA is a systemic analytical method to quantify flows and stocks of materials, good or substances in a well-defined system. MFA is an important tool to study the bio-physical aspects of human activity on different spatial and temporal scales. It is considered a core method of industrial ecology or anthropogenic, urban, social, and industrial metabolism. MFA is used to study material, substance, or product flows across different industrial sectors or within ecosystems. MFA is a central methodology of industrial ecology, quantifies the ways in which the materials that enable modern society are used, reused, and lost[90]. MFA can also be applied to a single industrial installation, for example, for tracking nutrient flows through a wastewater treatment plant. When combined with an assessment of the costs associated with material flows this business-oriented application of MFA is called material flow cost accounting. MFA is an important tool to study the circular economy and to devise material flow management. Since the 1990s, the number of publications in peer-reviewed journals related to material flow analysis has grown steadily[15]. The MFA methodology was explored in this thesis in two stages: First; to gain insight on material flow management studies as a tool to develop specific objectives for a more sustainable Aquaculture Salmon production in Norway; covered in paper I. Second, to develop a customized methodological approach to assess the food-loss in the NSVC and present alternative scenario for its reduction; covered in paper III.

3.2 Systems approach : Systems Engineering **(SE)** is a transdisciplinary, holistic, and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods[91]. SE is commonly applied in three combined modes: policy analysis, design, and management[92]. The SE usage of the terms "engineering" and "engineered" is in their widest sense: "the action of working artfully to bring something about". "Engineered systems" may be composed of any or all of people, products, services, information, processes, and natural elements[93]. SE focuses on: establishing, balancing and integrating stakeholders' goals, purpose and success criteria, and defining actual or anticipated customer needs, operational concept and required functionality, starting early in the development cycle; establishing an appropriate lifecycle model, process approach and governance structures, considering the levels of complexity, uncertainty, change, and variety; generating and evaluating alternative solution concepts and architectures; baselining and modelling requirements and selected solution architecture for each phase of the endeavor; performing design synthesis and system verification and validation; while considering both the problem and solution domains, taking into account necessary enabling systems and services, identifying the role that the parts and the relationships between the parts play with respect to the overall behavior and performance of the system, and determining how to balance all of these factors to achieve a satisfactory outcome. SE, and systems thinking were deployed in this thesis in two stages: **First**; to gain insight on the Norwegian Salmon production system, describe its structure, stakeholders, information flows and dynamics in relation to food-loss with systems terms and concepts, covered in paper II. **Second**, SE approach, specifically the six-steps method to gain insight on the integration of the SDGs framework within the system's stakeholders and decision makers; covered in paper IV.

4.0 Summary of published articles :

4.1. Paper I – Review of applying material flow analysis-based studies for a sustainable Norwegian Salmon aquaculture industry.

(Abualtaher, M. and Bar, E. 2020) Journal of Applied Aquaculture; 32:1,1-15
https://doi.org/10.1080/10454438.2019.1670769

This study aimed to detect patterns in previous material flow analysis-based studies. And how the outcomes of material flow studies were deployed to improve systems sustainability. A Systemic literature review, for MFA studies that were done on salmon production in Norway. The outcome findings from those studies were categorized according to which aspect of system's sustainability they address. 16 studies were selected and reviewed. There outcome findings targeted systems environmental impact, energy, technology, and feed improvement. Clear domination of the eco-centric aspects environment , energy , carbon footprint , ecological diversity, and integrity over the aspects of food loss, food security and ending hunger.

Contribution to the thesis

1-Material management plays a crucial role in systems sustainability.
2-MFA study to quantify food-loss is suggested for future research.

4.2. Paper II – Systems Engineering Approach to Food Loss Reduction in Norwegian Farmed Salmon Post-Harvest Processing.

(Abualtaher, M. and Bar, E. 2020) Systems. 8(1):4, https://doi.org/10.3390/systems8010004

Industrial Food loss is a systemic challenge. Requires system's understanding to reveal the interlinkages that caused the food loss. Research approached through the application of Systems thinking and Systems Engineering terminology to describe and analyze. Post-harvest processing excludes the rest raw material as they follow a different route separate from the food product. Product design and quality standards are the main drives for that exclusion
Food loss reduction is a systemic problem, its reduction requires a paradigm shift through new information flowing to the systems information pool. This study provided understanding for the systems structure, dynamics and revealed the hidden interlinkages in relation to food loss and system's efficiency as food and nutrients provider. Re-Introduced the definition of the harvested biomass through the stages of production based on experts knowledge and information.

Contribution to the thesis

1-Gained insight on how the system performs in relation to the food loss problem.
2-What are the main dynamics to influence the system toward food loss reduction measures.
3-There is a need for quantified information on the magnitude of the food-loss.

4.3. Paper III – Food-Loss Control at the Macronutrient Level: Protein Inventory for the Norwegian Farmed Salmon Production System.

(Abualtaher, M. and Bar, E. 2020) Foods, *9*, 1095. https://doi.org/10.3390/foods9081095

How food loss can be quantified and presented to the decision makers to cause the desired adaptation of food loss reduction. Research approached by a Substance flow analysis , where protein is the indicator substance. The rest raw material is seen in relation to their nutritional value and costs of production. Quantified approach provided the needed data to present an alternative scenario. Novel approach based on quantifying the macronutrient protein as an indicator substance on the material neutral from industry nor market definitions.

Contribution to the thesis

1-Customized method to assess the salmon RRM as food loss.
2-Presented an alternative scenario.
3-Supported the narrative with a model based on quantities.

4.4. Paper IV – Systemic Insights on integration of UN sustainable development goals within the Norwegian salmon value chain.

(Abualtaher, M. , Rustad, T. and Bar, E. 2021) Applied Sciences ; Special Issue Sustainable Aquaculture: Scientific Advances and Application. 1(24):12042.
https://doi.org/10.3390/app112412042

This study developed a conceptual framework to gain insight on the SDGs integration within the NSVC. The framework was developed by applying the systems engineering methods. The framework's application highlighted and analyzed the presence of the SDGs in corporate sustainability reports, academic curriculum, research, and governmental policies. This study revealed the system's drives to work on achieving the SDGs. NSVC is a globally expanded value chain with an organic relationship with global sustainability terms and schemes in general and SDGs in particular. The existing practice of corporate sustainability annual reporting was found to be a significant channel for SDG communication. The novelty of this study was that it proposed a mind-map to understand SDG integration within an industrial value chain abstracted into three concepts: commitment, communication, and performance measurability.
The study outcomes validated that UN SDGs framework is embraced by the NSVC and can be considered as a context for the sustainable development endeavor of the NSVC system. SDGs are present in education , in corporate sustainability reports and in Governmental policy.

Contribution to the thesis

1-The NSVC system have the motive and commitment to SDGs framework.
2-Esablished the concept that SDGs flow into corporate KPIs.
3-Reasonable to conclude that the system will seek measures for compliance with SDG 12.3.1 FL reduction in near future.

5.0 Discussion

This thesis start point observation is the salmon rest raw material that is being produced in huge quantities. A question about material that need to be managed in an alternative manner that meets with world needs for more food. The salmon rest raw material is a nutrient dense material and can contribute to global food security. The current uses of the salmon RRM to produce feed for pets and fur animals and few other uses do serve the concept of economical circularity, however those uses are not meeting its optimum potential to be used for food. Efficient utilization of the RRM relates to NSVC's sustainability and development. Reintroducing the salmon's RRM as systemic food-loss serve the cause of food security and the global sustainable development agenda. The interdisciplinary approach in this thesis allowed exploring this relation in depth and breadth. In general, interdisciplinary approach can bring the research closer to the truth when dealing with complex questions. Sustainability of human systems can be better understood by integrating concepts and indicators from multiple disciplines of knowledge[94]. Food systems science must embrace and engage with all relevant disciplines[95].This thesis integrated methods of material flow analysis MFA, systems engineering and system thinking principles in combination with sustainability narratives and the SDGs framework in a clear interdisciplinary approach. This study developed and demonstrated a scheme to localizing a global sustainability target (SDG 12.3.1 food-loss reduction) to an industrial production system at the operational level.

5.1 Material management for sustainable salmon farming

MFA studies investigate the metabolism of material within the system. The MFA family of methods were frequently used for understanding and evaluating sustainability[96]. Since this research is about material and its most sustainable usage, and to gain insight on the relation between material management within the NSVC and sustainability. The previous MFA studies conducted on NSVC were reviewed[15] and the findings highlighted the relation between material management and the multiple aspects for the sustainable development of the salmon industry. Several trends were detected: starting with the sustainability as a clear vision that the NSVC system is committed to, the role of the governmental stakeholder among multiple stakeholders in systems sustainability and the clear domination of the Eco-centric perspective of sustainability over the anthropocentric perspectives like; global hunger and food-loss challenges[16]. In practice the results showed that environmental, waste management, circularity solutions were applied on the salmon RRW, giving a hint on a research gap for investigating RRW's potential as food material. Material management is not only vital for reducing the environmental impacts of production, energy consumption and systems efficiency in general but also vital for food security and food waste/loss reduction[97, 98]. Paper I found that MFA-based methods can serve a role within a framework for food-loss reduction in the NSVC. That role rises from diversifying the objectives of MFA research to be more balanced and inclusive of the three pillars of sustainability: environment, economy, and society. MFA-methods can be customized to measure the size of the food-loss and reflect how the flow of RRM could be developed in an alternative scenario.

5.2 Systemic challenge

Food systems sustainability is a systemic challenge[99, 100], food-loss reduction is a systemic challenge as well[101]. The connection between pot-harvest processing byproducts and food-loss is a well-established concept adopted by the SDGs framework. To understand NSVC system structure in relation to the byproducts as FL challenge; a systems engineering SE study was done to gain insight. The SE study provided the proper terms to describe and understand the interlinkages, dynamics, and relations within the system's structure in response to the food-loss challenge[85]. This thesis gave significant weight to the system's stakeholders role in creating the context for the system's sustainable development. The insight from the systemic approach clarified reasons for the downgrade of salmon RRM to non-food uses. Paper II questioned the existing trade-offs and synergies within the NSVC in relation to RRM usages. Questioning the engagement between NSVC as food system and the feed production system is one of the main gained insights. Salmon RRM were perceived as waste[102] after being excluded from the **product design** and for **quality** non-compliance reasons. Those reasons were considered in selecting the proper indicator on food-loss as it must be independent from the existing material classifications within the industry. The indicator on food-loss need to reflect both the nutrients invested to produce the salmon RRM and the nutrient contained in it and not reaching human consumers. This gained systemic insight was a necessary precursor to develop a customized method to quantify the true food-loss and support the concept of food-loss reduction through alternative scenario for RRM utilization.

5.3 Protein inventory to measure food-loss

What could be the methodological approach to assess the size of food-loss in a certain food industry? An approach that reveals the system's hidden interlinkages and causative elements for food-loss. With an outcome result of assessment that is fit for consideration by system's decision makers. From this point came the third study, where the material was identified according to its content of the macronutrient (protein) considered as the indicator substance on material flow through the system. Moreover, approaching food-loss as a blockage in the flow of nutrients from nature to human food system, revealing both the true cost of producing this material and its true potential as food. To assess the actual food loss in the Norwegian farmed salmon production system in the year 2019 by quantifying the protein flows and stocks in the system. Paper III showed that the total invested feed protein is about four times more than the harvested salmon protein and about 40% of the harvested protein in the salmon biomass departs the human food chain by flowing to other non-food industries. Salmon RRM perceived as a systemic nutrient stagnation, where nutrients are being blocked from reaching the human food. This systemic stagnation was analyzed for its causative decisions and practices. Findings on protein content came in support for the argument that salmon RRW is a nutrient-dense food, and its best usage is to be developed into a food-product. The alternative scenario that turned 99% of the harvested protein into food product came with suggested changes in the flow of material and structure of the system. This scenario calls for a Paradigm shift in the scope of the system and the design of the process based on multiple production lines for multiple food products that consume all the raw material (harvested salmon). The question that came in response to the alternative scenario weather we can eat salmon RRM and how consumers will receive it ? in parallel with the question of why not? Two questions that are quality addition to the ongoing discussions on Salmon RRM best usage. Reviewing all the potential hazards in a well-preserved salmon RRM results no extra ordinary hazard from the salmon fish, except the physical hazard from the bones.

Common knowledge among food scientists that with basic physical processing (Grinding) combined with sufficient heat treatment (steam-cooking) this physical hazard can be eliminated. How about Consumer's appeal and preference ? There is a diversity in the world's culinary-cultures and the different fish parts are being used for food in different parts of the world[103]. Moreover, it depends on how the salmon RRM will be developed into a food product. This hypothetical food-product can't be judged only by one of its ingredients but also sensory qualities and price. The quality of the RRW, how well they are preserved and how quick they are processed are vital factors in keeping them safe for human usage(Food grade). Turning 100% percent of the RRM into food will face limitations for sure and might not be fully achievable. However, this study aims to introduce a narrative and a model for change to be part of the discussion on salmon RRM usage and future process design.

5.4 Sustainable development goals (SDGs)

Why will the system reconsider salmon RRM as food-loss and why food-loss reduction measures are a significant need for the system ? The answer rests in the fourth study that verified the UN SDGs framework integration within the NSVC. SDGs are adopted by the system's stakeholders as a guide vision to direct and influence the system's development toward sustainability. UN SDGs framework introduced the concept of responsible production and consumption (SDG 12) that is clearly demanding food-loss reduction. The insight from paper IV on how SDGs and their associated indicators eventually materialize as corporate KPIs and appear in system's policies and education is clear. Paper IV highlighted the role of the academic institutions as a stakeholder of the NSVC adoption of the SDGs framework. Paper IV validated that SDGs are adopted by the NSVC and by default the food-loss reduction target. Moreover, it is reasonable to forecast that NSVC seeking for food-loss measures will be on the agenda. The understanding for a specific food production system's role in global food security and its potential hunger reduction contribution. This understanding is important and needed locally and globally, and it will be needed more in near future to achieve food-systems reformation and compliance with the UN SDGs and Agenda 2030. The anchoring of salmon RRM utilization with the food-loss reduction target SDG 12.3.1 introduced a new approach to meet a food-system's challenge within a sustainability context. The NSVC have the motive and interest in turning the salmon RRM into a new food product. NSVC commitment to SDGs include an embodied commitment to food-loss reduction. NSVC communication, education and reporting are embracing SDGs. The Salmon RRM efficient utilization and the SDGs intersect in several common targets; most notably the food-loss reduction target.

6.0 Conclusion

The world has urgent need for food system's transformation toward sustainability. The world is less capable to afford food waste and food loss due to its rapidly growing needs for food and unmet food security aspirations. Norwegian salmon value chain is no exception, when approaching the utilization of salmon rest raw material, it is part of the system's sustainable development. It takes a lot of food to flow as raw material to produce a more expensive food like salmon, using only half of the fish for food is not serving any purpose for food security nor ending hunger and malnutrition. The usage of salmon rest raw material for food should be always part of the ongoing discussion regarding their best usage. Systems engineering (SE) and Material flow analysis (MFA) methodologies were effective in investigating the systems structure and decision making over the material usage. Salmon RRM have been classified and handled as waste or secondary material; in this thesis it is a post-harvest food loss. Through the combined insights emerging from the conducted research, this thesis conclude that UN SDGs framework is an existing guiding context for NSVC development. UN SDGs provided the terms and concepts needed to create a solution for one of the NSVC system's challenges, the rest raw material.

7.0 Novelty and contribution

- Re-identified the Salmon rest raw material as food-loss as in SDG 12.3.1 .
- Emphasized the role of the multiple stakeholders in NSVC sustainable development.
- Developed a customized method: **FL control at macronutrient level**, for industrial food-loss assessment based on a systemic inventory for the protein.
- Introduced Protein as an objective indicator-substance on the size of food-loss.
- Presented an alternative scenario for post-harvest processing that serves global food security and SDGs fulfillment at an operational level.
- Developed the **TCSAS** framework to gain insight on SDGs integration in value chains. This framework can be applied on other value chains.

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Appendix

Paper 1

Review of applying material flow analysis-based studies for a sustainable Norwegian Salmon aquaculture industry

Mohd Abualtaher &Eirin Skjøndal Bar

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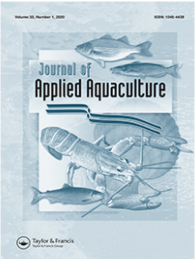

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Review of applying material flow analysis-based studies for a sustainable Norwegian Salmon aquaculture industry

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ABSTRACT

Since its beginning in the early 70thies, the fast growing Atlantic salmon aquaculture industry in Norway has been and still is an object for research across numerous disciplines and research fields. This article presents an overview of the research studies applying Material Flow Analysis (MFA) based methods on Norwegian Aquaculture of Atlantic Salmon starting from 2004 until 2018. The studies were reviewed in relation to their applied method, involved institutions, flows, data acquisition, and suggestions for improvement. All of the reviewed studies applied different MFA methods suitable to the objective of each study, were done with involvement of multiple institutions and stakeholders, modeled credible data and provided specific suggestions for reducing the environmental impacts and optimizing nutrients utilization efficiency. The review concludes that MFA-based methods have the potential for having a functional role within the framework of the Norwegian Salmon Aquaculture industry's sustainable development. A key factor in fulfilling that potential would be diversifying the objectives of MFA research to be more inclusive of the three pillars of sustainability: environment, economy, and society.

KEYWORDS

Salmon; material flow analysis; aquaculture; sustainable development; Norway

Introduction

Background

Today, aquaculture is a major global supplier for seafood, a significant contributor to the human food security and the fastest growing food production sector in the world (FAO 2018). United nation's food and agriculture organization reported that the total aquaculture production is representing about 53% of the total seafood production in the world, and it is continuously growing in contrast to the wild capture fisheries production that remains almost the same for the last 30 years (FAO 2016). Norway is globally ranked second major exporter of fish and seafood products to the global market (FAO 2018). Aquaculture of Atlantic salmon (*Salmo salar*) in Norway is a significant contributor to the economy; in

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/wjaa.

2016 it made a total export revenue of NOK 61.5 billion as mentioned in the Norwegian aquaculture analysis report (Ernst&Young 2017).

Aquaculture is a rapidly growing food production sector exploiting ecological resources. The major challenges facing the Norwegian salmon farming sector are: reduction of fish escape to the wild, combating infection with sea lice, reduction of water pollution, implementing regulations(Bergheim 2012). Salmon aquaculture in Norway is relying on imported feed ingredients from South America (Ytrestøyl, Aas, and Asgard 2015). The long supply chain of feed ingredients increases the cumulative energy costs and environmental footprint of this industry. Norway is committed toward sustainability and environmental footprint reduction of all its industries and officially engaged in several international agreements through the Kyoto protocol and Paris agreement. The growing trend of preferences among consumers worldwide for a food product with minimum adverse effects on the Environment (de Boer 2003) requires more research for assessing the environmental impacts of salmon aquaculture. Norwegian salmon aquaculture production is considered as having a lesser impact on the environment compared to salmon farming in other countries (Pelletier et al. 2009). Aquaculture feed material global consumption in 2008 was 30 million tons and expected to grow to reach around 71 million tons in 2020 (Tacon, Hasan, and Metian 2011). The rapidly growing demand for fish feed demands an efficient use of feed material and optimizing the feed conversion rate. Research sponsored by the Norwegian government assists the industry to face up to its challenges and limitations. (Asche et al., 1999; Chu et al. 2010).

Aquaculture research and sustainable development; Norwegian perspectives

The aquaculture production sector in Norway aims at profitability, competitiveness and sustainable development (Aquaculture-Act 2005). This developmental strategy for the salmon aquaculture industry in Norway is underpinned by a governmentally prioritized and supported scientific research (Strategy 2007). In addition, the Norwegian stand on development is guided by a national agenda that takes objectives from the global vision of 2030 Agenda for Sustainable Development Goals (SDGs). Norway's follow-up on Agenda 2030 for sustainable development goals is committed to work with international organizations to preserve the oceans as a global sustainable resource (Ministries 2016). Based on that commitment to these global visions for sustainable development, Norwegian institutions contributes their share to FAO's development of norms & standards for sustainable aquaculture management (Report 2017). Norwegian aquaculture industry and research institutions adopted the global sustainability goals and their measurable targets as part of the aquaculture sustainable development strategy. Material flow analysis (MFA) methodology was applied to evaluate the sustainability of salmon aquaculture production system in order to define measures that will improve its efficiency.

The MFA methodology

Material flow analysis (**MFA**) was developed as a systematic assessment of the flows and stocks of materials within a defined system (Brunner and Rechberger 2005). MFA is a broad concept and a family of methods (Balat 2004). The methods differ according to their purpose, system boundaries and the modeling of material flows within an entity or sub-entity; whether its goods, substances or nutrients. Substance flow analysis method **(SFA)** deals exclusively with identical units of matter homogeneous in qualities. Another MFA method is the Life Cycle Assessment **(LCA)**: a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy with the associated environmental impacts directly attributable to a product or service system throughout its life cycle. LCA has a documented standardized technical framework laid out by the International Organization for Standardization (ISO 2006). MFA-based methods have been applied on different production systems and they had proven capacity to generate information on resources, environmental pollution and waste material (Binder, van der Voet, and Rosselot 2009).

The role of MFA methods in sustainable development was described in four connection points: (1) providing supporting database and information needed to formulate measures to increase the efficiency of waste recycling, reduce resources extraction and emissions; (2) finding out where the losses or inefficient usage of resources happens, identifying key materials or products for environmental policies formulation and sustainable environmental planning and management; (3) defining indicators on the flow of materials for increasing recycling levels and minimizing the wastes, giving direction on the efficient use of resources; (4) increasing the usage of the materials by modeling the socioeconomic responses (Huang et al. 2012).

MFA modeling of a food production and consumption system will assess the economic, environmental consequences, changes in patterns of food consumption and will serve as a practical tool for planning (Risku-Norja and Maenpaa 2007).

LCA was applied on several food products since early 1990s (Andersson, Ohlsson, and Olsson 1994) and later on seafood products (Ziegler et al., 2003) for the purpose of assessing the environmental impacts of the food industry and defining measures to reduce those impacts. Early LCA studies on Aquaculture were published in 2004 by (Papatryphon et al. 2004) and in the same year in Norway (Ministers 2004). However, even though MFA-based methods have shown promising results, there are some limitations and common critiques, mainly about errors and uncertainties rising from data gaps and lack of knowledge, the degree of data reconciliation, modeling choices and mistakes, non-verified imputations and variations between different measurement methods (Patrício et al. 2015). The most significant limitation is attributable to the fact that MFA depends less on empirical observation but rather on collective social constructed knowledge (Meylan et al. 2017). The reliability of the MFA outcomes is dependent on the quality of the used data. The sources of the secondary data used in the MFA model might be to a certain extent an indicator on the data truthfulness, accuracy and relevance.

Review method

Number of peer-reviewed journal papers and official institutional reports concerning MFA-based studies on Norwegian salmon aquaculture were reviewed. The main aim is to identify trends and directions in the research related to the Norwegian salmon aquaculture industry as well as the MFA methodology and resulting suggestions for sustainable development of this sector. The orientation of this study lies within the systematic literature review methodology.

The literature search were limited to peer-reviewed journal articles and official institutional reports. The basis for the literature search was the Web of Science online database (http://webofknowledge.com), and Scopus (https://www.scopus.com), using following keyword: Norway, salmon, aquaculture, and one of the terms LCA, LCS, MFA, SFA, and NFA. In addition, the same keywords were entered in to the search engine Google Scholar (https://scholar.google.com), in order to crosscheck the findings and broaden the search.

The selection of the studies was according to several integrated criteria:

(1) It is a MFA-based study.
(2) It is an aquaculture production system for Atlantic salmon (*Salmo Salar*).
(3) It illustrates applicable suggestions for sustainable development.
(4) It is applied on a Norwegian production system.

Selection on these criteria retained 16 papers.

The overreaching research questions guiding this literature review study where:

- what are the overall sustainability objectives in MFA-based research studies in the Norwegian salmon aquaculture industry?
- what elements shaped the context of the reviewed studies for instance, namely, the involved institutions and stakeholders, sources for data and information and the directed motive for sustainability?
- what are the main areas of improvement identified on the strength of the outcomes of the reviewed MFA-based studies conducted on the Norwegian salmon aquaculture industry to make it more sustainable?

A preliminary systematic analysis of the selected body of literature indicated as important factors: applied method, study's objectives, investigated materials, data acquisition and the outcoming suggestions for improvement categorized and discussed. These factors guided the review described here-under and illustrated in Figure 1.

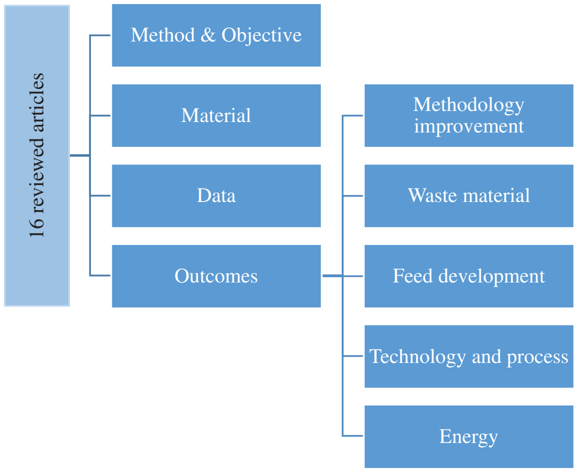

Figure 1. Review structure: The retained 16 studies reviewed according to this structure.

Discussion of findings

The selected MFA studies were expanding from 2018 on backward with no findings earlier than 2004. The general context in the reviewed MFA studies is seeking sustainability in Salmon farming mainly through reducing the ecological impacts and increasing the system's efficiency. Norwegian governmental leadership role in aquaculture research and development is significant and motivated for addressing relevant environmental issues (Chu et al. 2010). The global agenda for sustainability is taking part in shaping the context of the reviewed studies and contributing to their content. International organizations like FAO-UN with its reports are commonly referred to as source for information and the IFFO organization its data, statistics, and the international standards organization for its ISO 1440 standard for the LCA method. A detailed look at the reviewed studies revealed patterns and interrelations between the studies objectives, methods, data sources, and the context of turning this industry to a more sustainable production sector is socially and governmentally driven.

The applied methods and studies objectives

The reviewed studies developed structured systematic models based on quantifying the material flow in the system. Researchers analyzed and discussed those models according to the stated objective of each study. Table 1 summarizes the reviewed studies according to the applied method and its objective. Twelve of the 16 reviewed studies were applying LCA method with environmental impacts. Moreover, LCA standard method include a final interpretation phase to identify conclusive well-substantiated findings to lower the environmental impacts of the assessed system. Only few research papers were dealing with

Table 1. The methods applied in the selected studies.

Author & year	Method	Objective of the study
Ministers (2004)	LCA	Introduce LCA as an environmental assessment method for Nordic seafood products.
Ellingsen and Aanondsen (2006)	LCS	Assess environmental impacts of Salmon farming in comparison with chicken and cod from capture fisheries.
Ellingsen, Olaussen, and Utne (2009)	LCA&LCS	Seafood-oriented environmental analysis, preliminary study of CO_2 emissions from Norwegian farmed salmon.
Winther et al. (2009)	LCA	Quantifying carbon footprint and energy use of Norwegian seafood products including improvement options
Boissy et al. (2011)	LCA	Assess environmental impact of marine ingredients with plant ingredients in Salmonid feed.
Hognes, Sund, and Ziegler (2011)	LCA	Carbon footprint and area required to produce 1 kg of Norwegian salmon.
Torrissen et al. (2011)	LCA	Sustainability of salmon aquaculture production.
Ytrestøyl et al. (2011)	LCA	LCA for resource utilization and eco-efficiency of salmon farming in Norway
Ford et al. (2012)	LCA	Identifying local ecological impacts of salmon farming.
Hognes et al. (2012)	LCA	To map the environmental hotspots in the farmed salmon production system.
Ziegler et al. (2013)	LCA	Carbon footprint evaluation in comparison with other seafood products
Ytrestøyl, Aas, and Asgard (2015)	NFA	Farmed salmon nutrients retention, and feed marine ingredients utilization.
Cashion et al. (2016)	LCA	LCA method improvement concerning marine resources usage.
Hamilton et al. (2016)	SFA	Holistic mapping for the flow of phosphorous in the sectors of aquaculture, agriculture and fisheries.
Aas and Åsgård (2017)	NFA	Nutrients and energy content of feed spills and fish feces (sludge) of salmon farming in Norway
Philis et al. (2018)	SFA&MFA	Energy and phosphorous consumption comparison between using seaweed vs. soya protein for salmon feed

nutrient-substances, despite the fact that salmon farming pertains to the food production sector.

For the first nine consecutive years, MFA application was limited to LCA, a steady trend initiated in the earliest study found. This study was a project of the Nordic Council of Ministers that stands as a milestone as the methodology of LCA for environmental impacts assessment of aquaculture was presented, discussed and method adopted (Ministers 2004).

First nutrient flow analysis (NFA) study (Ytrestøyl, Aas, and Asgard 2015) included in NOFIMA (Norwegian governmental research institution) report investigated the flow of nutrients like: protein, lipids, omega 3 within farmed salmon production system and the efficiency of their utilization. Two years later NFA study targeted the feed spill, i.e. uneaten feed and the salmon fish feces ending up as bottom sludge with a significant content of nutrients and energy as waste (Aas and Åsgård 2017). The study discussed potential improvements to reduce this loss and importance of choosing NFA method for modeling the nutrients flow within the system. The MFA methods were frequently used for comparison purposes, for example, Ellingsen and Aanondsen (2006) conducted a comparative LCA study of the environmental impacts of Norwegian cod fishing, Norwegian salmon aquaculture and Norwegian chicken farming for meat. The study aimed at defining references for comparison and areas for potential improvement with respect to environmental performance. Boissy et al. (2011) published an LCA study to compare the ecological impacts of plant-based feed for farmed salmon vs. a standard feed made with fishmeal and fish oil ingredients. Philis et al. (2018) did MFA/SFA study to compare the phosphorus and energy consumption between using seaweed protein vs. soybean protein as feed ingredients for salmon aquaculture. One of the common objectives of the LCA studies is methodology development. Cashion et al. (2016) reviewed several LCA studies and suggested a modification of the method; specifically the calculation of the primary production rate. The study demonstrated the suggested modification by applying it on a model of the marine-derived inputs in Norwegian salmon aquaculture feed production. Another LCA study defined new local potential environmental indicators for all the production stages of salmon farming, proposed them to be included in future LCA studies (Ford et al. 2012).

Application of SFA method targeting a specific substance flowing through the Norwegian salmon aquaculture system is relatively recent. A landmark SFA study targeted phosphorous flow in Norway done by researchers at the Norwegian university of science and technology (NTNU). The study came up with a holistic model that integrated the sectors of aquaculture, fisheries, and agriculture aiming toward a multiple systems-wide phosphorus management by identifying the inter-sectoral synergies (Hamilton et al. 2016). Two years later, in 2018, another SFA study was done in the same institution (NTNU) and SFA was applied for comparison between two feed ingredients as alternatives to each other (Philis et al. 2018).

The timeline of the reviewed studies in Table 2 reflects the trend in the study objectives to become more specific to details and more diverse with methods, clearly due to the accumulation of published knowledge and the academic direction toward investigating further areas.

Targeted materials and substances

The studies discussed the flow of material and substances within the salmon farming industry. Each study defined certain material or substance to trace according to the scope and objective of the study. Substances like: phosphorous, nitrogen, omega-3, fatty acids of DHA, EPA, pigments (astaxanthin) were present in the reviewed studies. Goods and materials like: salmon feed mix (feed pellets); plant-feed ingredients, fish oil, rapeseed oil, soya beans protein concentrate, fishmeal, seaweed protein concentrate, fish scrap, sludge, and the Salmon fillet product were studied and their quantified flow was modeled and analyzed. No studies found targeting any material nor substances outside from

Table 2. Categories of out coming suggestions for salmon farming sustainable development.

Author & year	MFA method	Methodology improvement	Technology & process	Energy	Waste & nutrients recovery	Feed development
(Ministers 2004)	LCA	X				
(Ellingsen and Aanondsen 2006)	LCS			X		
(Ellingsen, Olaussen, and Utne 2009)	LCA&LCS	X				
(Winther et al. 2009)	LCA	X				
(Boissy et al. 2011)	LCA	X				X
(Hognes, Sund, and Ziegler 2011)	LCA	X				X
(Torrissen et al. 2011)	LCA		X			X
(Ytrestøyl et al. 2011)	LCA			X		X
(Ford et al. 2012)	LCA	X				
(Hognes et al. 2012)	LCA	X				X
(Ziegler et al. 2013)	LCA	X		X	X	
(Ytrestøyl, Aas, and Asgard 2015)	NFA	X	X		X	X
(Cashion et al. 2016)	LCA	X				
(Hamilton et al. 2016)	SFA	X			X	
(Aas and Åsgård 2017)	NFA		X		X	
(Philis et al. 2018)	SFA&MFA			X		X

the food chain, for example, any specific chemical contaminants, pesticides, herbicides, antibiotics or heavy metals that could possibly exist within the salmon farming value chain.

Data sources and quality

The reviewed studies used data obtained from multiple sources. By looking into the data acquisition and the sources of the used secondary data, this study is pointing out to the issues of data credibility, accuracy, and relevance. The studies acknowledged several national highly credible institutions for providing material inventory lists, statistics and results for the research. Such institutions are valid sources for information. The studies about salmon feed material and its composing nutrients relied heavily on data and information from the private sector feed manufacturers who are well established in the market as large-scale corporate suppliers, a sign of cooperation and involvement of a major stakeholder in the development of the Aquaculture industry in Norway. Data regarding imported plant-feed ingredients like soya beans were collected from lists published by international organizations like UN-FAO, Marine ingredients international organization (www.iffo.net), and from the major corporate suppliers in the market. The data were processed and modeled accordingly. However, the variability of data sources were each parameter comes with a level of uncertainty will lead to accumulative uncertainty in the final model (Philis et al. 2018). From early reports, it was stated that the method is limited by an extensive uncertainty due to a lack of data on certain parts of the system (Ministers 2004).

For example, the lack of sufficient data about food processing and post-consumer food wastes (Hamilton et al. 2016), the absence of sufficient data on the nutrients composition, as not all feed ingredients have been analyzed to their content of substances; in this case, the developed models are partly based on estimated values (Ytrestøyl, Aas, and Asgard 2015). All these shortcomings contribute to the uncertainty of the conclusions on these assessments. Five studies out of sixteen obtained primary data, one used chemical analysis, and the other four used direct correspondence and interviews. Besides the issues of data insufficiency and data gaps, the quality and accuracy of the available data is a legitimate question. There is an absence of a standard verification protocol for the secondary data, either by chemical analysis for samples or to be crosschecked with data from another source. Significant points raised in the reviewed studies regarding data statistical reconciliation and error propagation analysis (Cashion et al. 2016). For data processing and modeling the reviewed studies relied on computer software; Microsoft Excel for primary processing followed by secondary processing and modeling using SimaPro for LCA studies, STAN for SFA study (Hamilton et al. 2016) and eSankey for SFA/MFA study (Philis et al. 2018).

Outcomes

All of the 16 studies reviewed gave suggestions for efficiency improvements and sustainable development based on the outcome of each study. The suggestions were grouped within following categories: improvement of methodology, technology and process, energy, waste & nutrients recovery and feed improvement, summarized in Table 2. Some studies came up with suggestion falling under one category, other studies with more suggestions under up to four categories. However, some other general developmental suggestions that do not fall under the categories of Table 2 were briefly discussed; i.e. process management, directing investments, and association with other sectors.

Methodology improvement

Eleven of the 16 reviewed studies suggested modification of the applied MFA method to customize and include technical and environmental criteria. A 2004 report of a Nordic Network project issued/funded by the Nordic Council of Ministers the governments of the 5 Nordic countries took the initiative to conduct the first LCA on the aquaculture industry. Leading to the conclusion: (i) there is a regional strategic vision for aquaculture's sustainable growth and expansion, and (ii) adoption for **LCA** as a standard method for the assessment of aquaculture environmental impacts (Ministers 2004). In a clear trend, nine of the 12 LCA & LCS studies came up with suggestions for the improvement of the method mainly to include local environmental impacts attributed to farmed salmon products in Norway.

Ford et al. (2012) developed indicators of ecological impacts associated with the production stages of salmon farming to be included in life cycle impact assessment (LCIA) of any future LCA study, giving the method grounding in the ecological context. In their LCA report, Hognes et al. (2012) suggested including the feed micro-ingredients for a more accurate total carbon footprint assessment; this is a development on the methodology from previous LCA report done earlier by the same institution (Hognes, Sund, and Ziegler 2011). Cashion et al. (2016) analyzed the use of the primary production required (PPR) in LCA studies as indicator to assess the sustainability of the ecosystems where salmon feed marine ingredients are harvested from. Suggesting a more refined method that considers the specific species harvested for fishmeal and oil yields, the source ecosystem-specific transfer efficiencies and results expression as percentage of total ecosystem production. The modification was demonstrated through a comparison of results before and after applying this methodological improvement.

Nutrient flow analysis (NFA) study discussed the most suitable MFA method to evaluate the sustainability of the salmon farming system and reached a highlighted conclusion that it would be SFA or NFA rather than LCA. The commonly used functional unit of weight and mass balance in LCA method does not reflect the qualitative change in the nutrients content that the process is causing. The study recommended including the retail chain in the boundaries of assessing this production system because most of the food waste take place after the product departs the farm gate, assessment of the retail product-handling practices might be justifiable. SFA study targeting phosphorous assured on the importance of locating the spatial and temporal distribution of the targeted indicator substance. Consideration that practically raised the methodology above its typical application on a single sector, and tracing the substance to other sectors. Expanding the modeled system boundaries over multiple sectors of aquaculture, fisheries and agriculture lead to defining the phosphorous flow linkages and synergies between the different sectors revealing potentials for tradeoffs (Hamilton et al. 2016).

Technology & process

Three studies pointed toward the need for technological improvements on the equipment to account for losses in material. The **NFA** Study by Ytrestøyl, Aas, and Asgard (2015) discussed the loss of nitrogen and phosphorous due to uneaten feed and how it is affecting the marine ecosystem. The report pointed out the need for further hydrodynamics technological improvements on the feeding systems and the importance of developing better effluent filtration systems as the way to reduce the amount of feed spills. Aas and Åsgård (2017) mentioned the Sludge dewatering technology, sludge treatment, and the need for more efficient feeding systems as technological improvements to optimize nutrients utilization. Nutrients circulation within the system is the parameter to evaluate the performance of the feeding technology, clearly for environmental and economical perspectives. Torrissen et al. (2011) specifically discussed the open cage systems technology for salmon farming and its impacts on the environment and the biodiversity making an informed call for the improvement of the process toward better control over the flowing out feed spills and escaped fish.

Energy

The energy consumption, the associated carbon footprint, and their reduction were targeted and discussed in four reviewed studies. To lower the carbon footprint of the product they suggested for instance, the use of hydropower, largely available in Norway; the use of heat generated by incineration plant to compound feed (Philis et al. 2018). The carbon footprint of the salmon aquaculture production system is mainly determined by the quantity and type of the feed ingredients (Ziegler et al. 2013). Other researchers looked into aquaculture's associated cold transportation; favored liquid natural gas as more efficient fuel over diesel, uses of the sludge for the production of methane as a source of energy (biogas). The modeling of the materials flowing in and out of the system and the quantification of its carbon footprint discussed alternatives and tradeoffs.

Waste and nutrients utilization

In four studies, the flow of the salmon feed material was modeled. The nutrient balance of macro-nutrients and micro-nutrients within the production system, i.e. the amount fed, retained, excreted, wasted, is assessed. The SINTEF report 2012 mentioned the extraction of fish oil out of salmon by-products at the rate of 9% as given by Hordafor (private sector Norwegian feed ingredients producing company); raising the question if this form of extraction is applied in all salmon post-harvest processing factories. Nutrients loss is associated with ecological problem of eutrophication; that appeared clearly in different LCA studies. NOFIMA a research institute funded by the Norwegian government reported in 2017 the quantity of 11,251.142 tons of dry matter sludge coming off the Salmon Aquaculture production in Norway. The sludge came mainly from feed spills and fish-feces. The lack of utilization of the sludge as a source of nutrients makes the system distant from being a closed-loop materials cycle by the industrial ecology's definition, the report clearly provides suggestions for improvement starting from increasing the digestibility of the feed suggesting a detailed amendment of removing indigestible carbohydrates as a recommendation for the feed manufacturers. However, the report stressed developing the feed system, effluent collecting, and sludge dewatering and filtration technology. A model for minimizing the losses of phosphorus has been established (Hamilton et al. 2016) phosphorous is a valuable micro-nutrient.

Feed development

Seven studies modeled the material flow in and out the system, quantified the environmental effects; for the objective of defining alternatives to develop the salmon feed. Studies were able to present numerical data favoring certain alternative ingredients with less environmental impacts plant-based ingredients were suggested to replace fish oil and fish meal as an alternative with lower environmental impact (Boissy et al. 2011). A study discussed several feed ingredients, including resource intensive agricultural inputs such as soy, sunflower meal, wheat and corn gluten considering their growing, transport and processing energy costs; they might not have a lower carbon footprint than their marine substitutes (Hognes, Sund, and Ziegler 2011). The environmental costs of the micro-ingredients, and the freshwater footprint of the plant ingredients are brought to the discussion as considerable factors (Hognes et al. 2012). A study found that using marine ingredients for salmon feed is more sustainable option if fishmeal is produced from seafood processing byproducts and from well-managed small pelagic fisheries (Torrissen et al. 2011). (Ytrestøyl et al. 2011) raised questions regarding the most efficient route for the flowing nutrients within the salmon industry. The frequently acknowledged involvement of the major feed manufacturers in Norway in providing their data for the reviewed studies reveals a level of cooperation between research and industry.

Conclusions

There is a clear role for the MFA-based methods as a tool to develop specific objectives for a more sustainable Aquaculture Salmon production in Norway. The reviewed studies provided a quantified outcome that is supporting applicable measures on specific areas that are in need for further improvement. The MFA-based studies conducted in Norway between 2004 and 2018 came up with suggestions and considerations in the areas of lowering the environmental impacts, feed development and improving efficiency of nutrients utilization. Significant contribution to the systems information pool and guiding knowledge. However, applying the MFA methodology to address specific objectives relevant to fish post-harvest processing and optimum nutrients extraction was not at the center so far with a dominance of the environmental objectives. This could be a fertile area for future MFA research; were food security and minimizing post-harvest processing food loss are the main objectives. Several studies fall in a steady trend to customize the MFA-based methods to fit the local context and face up its requirements.

This review remarks the diverse involvement of multiple stakeholders and contributors in the reviewed MFA-based studies, involvement that can be described as a structural framework for the ongoing research and development of the salmon aquaculture production sector in Norway.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Paper II

Systems Engineering Approach to Food Loss Reduction in Norwegian Farmed Salmon Post-Harvest Processing

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Article

Systems Engineering Approach to Food Loss Reduction in Norwegian Farmed Salmon Post-Harvest Processing

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Abstract: The United Nations 2030 Agenda for Sustainable Development set the target of halving per capita global food waste and reducing food losses, including post-harvest losses. Food loss is a significant global challenge rising from the decrease in food quantities available for human consumption because of decisions and actions taken by food manufacturers and suppliers before it even reaches the retail market. Food loss within the Norwegian farmed salmon post-harvest processing system could be reduced by making change in the system's behavior. This study, by following systems engineering principles, aimed to develop insight into the salmon post-harvest processing system's behavioral dynamics causing current food loss and to consider conceptual keys to solutions. This study tied the food loss problem to systemic behavior of byproducts downgrading to non-food uses as the major cause. The decisions made on the materials flow are based on product design, quality control, and environmental solutions. Making a decision to conserve byproduct materials by prioritizing keeping them within the human food chain requires supportive data on their true potential as a food source. The system's information pool that decision makers rely on can be fortified with the system's engineering multidisciplinary outcomes that will enable the necessary paradigm shift to achieve the quested food loss reduction.

Keywords: Atlantic salmon; byproducts; post-harvest processing system (PHPS)

1. Introduction

The United Nations food and agriculture organization reported that one third of the global food production goes for waste, an estimated annual worth of 1 trillion USD, and environmental costs of 3.3 Giga-tons of greenhouse gas emissions [1]. In seafood production, the estimated loss is about 35% of the total production. Such a high loss has a multiple negative impact on food security, economy and environment [2]. Sustainable development goal (SDG) number 12: Responsible consumption and production; set the target number 12.3 that aims, by 2030, to reduce by half the global food waste per capita at the retail, consumer levels and reduce food losses along production and supply chains, including post-harvest losses. Setting up such a target by the United Nations reflects a global consensus on the significance of the problem, importance of the target and the achievability of this target. Food losses are the commonly used term to describe the decrease in edible human food material throughout the part of the supply chain that is designated specifically to produce food for human consumption such as food production systems and postharvest processing systems [3]. The post-harvest processing system (PHPS) is a set of activities applied on the output material of an agricultural production system not limited to plant production but including all kinds of animal production systems such as meat, dairy, bees-honey, aquaculture and fisheries. Post-harvest activities are dependent on the nature of the product but commonly include transportation, storage, sorting, processing, packaging and delivery to retail. PHPSs are structured on several elements that work together and aim to convert the received material into a human food product, safe for consumption, with nutritional content and market value. Any change requested from PHPS to optimize efficiency, adjustment of practice or adapting to a new paradigm requires by a complete analytical understanding of the system, the logic it is operating under and its influencing circumstances. Moreover, resources allocation through the PHPS can draw a clear picture of the system's performance. System metabolism of the material through processes and practices determines the size of food losses. Systems understanding can result in a set of qualitative and quantitative information on existing food losses and points of adjustments for their reduction.

The harvested food material flowing through the PHPS starting as a raw material and ending up as product go through transformational technical processes. The system treats the material according to several requirements: feasibility, quality standards, available technology, environmental demands and health restrictions. This necessitates a multidisciplinary approach for understanding the dynamics that influences the system and material. Therefore, any counter approach that overlooks the diverse sources of information that governs the systems behavior is not expected to result a holistic solution that appeals to the variable interests of the system's stakeholders. Consequently, it is not expected to overcome the systems homeostasis nor achieve the desired adaptation.

1.1. Norwegian Salmon Farming (Background Information)

Atlantic Salmon *(Salmo Salar)* production value chain in Norway is a mature industry that started in 1970. It has earned a pioneering economical role and high social significance as a national source of income, global contributor to the seafood market and aquaculture technology development. At the same time, it is operating in a governmentally well protected environment and conserves natural resources. Salmon is a main commodity in the Norwegian food market and for export as well.

The aquaculture production sector in Norway is regulated toward profitability, competitiveness and sustainable development [4]. The framed salmon value chain starts from salmon feed production used for salmon aquaculture and finally, the PHPS of the harvested salmon, as Figure 1 demonstrates.

Figure 1. Norwegian farmed salmon value chain.

Aquaculture is the fastest growing food production sector in the world and Norway is the second major exporter of fish and seafood products to the global market [5,6]. In 2018, Norway exported 2.5 million tons of seafood (salmon, trout, cod, clip fish, herring, king crab, prawns, and mackerel) with a revenue of 90 billion NOK [7]. In 2017, Aquaculture exports revenue was 61.5 billion NOK [8] where 94.5% of the Aquaculture production was Salmon [7]. The quantity of the harvested salmon in 2018 was 1,281,872 tones [7]. Salmon aquaculture is an intensive production system based on biotechnology science [9] and it aims to produce nutritious seafood for human consumption. Since its beginning in 1970, the development of this industry has been a persevering endeavor carried out by multiple institutions that has continuously addressed environmental impact challenges and sustainable development. The wide involvement of establishments and stakeholders, ranging from private sector companies to academic institutions, regulative authorities, research institutions, associations, and global institutions, creates diverse contribution to the pool of knowledge in relation to the sustainable development of this sector. Norway is committed to the global Agenda 2030 for Sustainable Development and its 17 Sustainable Development Goals (SDGs), through the deployment of resources and efforts to make the desired changes and achieve the goals as assured by the Norwegian government in the official agenda 2030 follow-up statements. Food waste reduction falls at the heart of SDGs 2 and 12 [10].

From the previous research, it is clear that Salmon aquaculture production in Norway has a well-monitored cost, both environmental and financial, leading to the conclusion that the harvested Salmon is a worthy biomass and the demands for it to be efficiently processed and utilized to the maximum level are reasonable from several perspectives. However, a major portion of the harvested Salmon mass does not end up as food products [2,11–13] but instead, as waste material or processing by-products that, in the best cases, go to other non-food uses and can be counted as a food loss.

1.2. Food Loss Reduction Challenge

The United Nations made a global commitment for the 17 sustainable development goals to be achieved by the year 2030, in a global platform known as Agenda 2030. Sustainable development goal number 12 (SDG 12) is responsible consumption and production by ensuring sustainable consumption and production patterns. Under SDG 12 falls target 12.3 (Table 1); which aims, by 2030, to halve per capita the global food waste at the retail and consumer levels and to reduce food losses along food production and supply chains, including post-harvest losses. The target is specified by the measurable indicator 12.3.1—Global food losses, which has two sub-indicators 12.3.1, including the Food Loss Index (FLI), which focuses on food losses that occur from production up to (and not including) the retail level and measures the changes in percentage losses for a basket of 10 main commodities by country in comparison with a base period, and sub-indicator 12.3.1 b, which measures Food Waste, which comprises the retail and consumption levels. Both sub-indicators will contribute to measuring progress in reducing food loss and food waste toward achieving SDG target 12.3.

Table 1. Summary of UN 2030-Agenda related terms used in this study.

UN 2030-Agenda	Global transformation toward sustainability 17 Sustainable Development Goals (SDGs)
SDG 12	Ensure sustainable consumption and production patterns This goal is interpreted to 11 Targets.
Target 12.3	Halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses. Target has one measurable indicator on its performance; that subdivides for two sub indicators.
Indicator 12.3.1	Sub-indicator A-Food Loss Index (FLI), Production
	Sub-indicator B-Food Waste Index (FWI) Retail & consumption

The scope of this study is focused on food loss reduction at the post-harvest processing stage. The UN agenda 2030 in general, and target 12.3 specifically, provide general guidance on addressing the food loss problem and achieving targeted reduction. Reviewing target 12.3 specifications provided accurate definition for the problem and clarified distinctions between the different categories of food waste. Target 12.3 suggested some guiding concepts to approach this challenge, such as that it is a system-level problem, measuring material and change needs to be holistic, and considerate to the system's stakeholders and the three elements of sustainability (environment, economy and society). The definition of (PHPS) food loss applies to not only the losses in final food product intended for human consumption but also the associated inedible parts, which usually depart the human food supply chain as by-products. Target 12.3 is equally concerned with food security and resource-use efficiency [14]. The targeted reduction, if achieved, could help in addressing the food production-associated environmental impacts and contribute to hunger relief through a higher efficiency of the agri-food systems [15]. Food loss does not only decrease the quantity of available food for human consumption but also lowers the availability of the natural resources required to produce food. This fact is becoming more important with time due to the growth of the world population, which is estimated to be more than 30% increase by the year 2050 [16]. The reduction of post-harvest loss can advance the sustainability of the food value chain from economic, social, and environmental perspectives [17]. Food loss in the production segments of the food supply chain is caused either by the way in which the production system functions or its institutional and legal framework [18]. Defining food loss causing practices requires measurements for quantities tied to each practice or process. Causes relevant to the institutional and legal framework require understanding of the social and economic context; moreover, defining the involved stakeholders and allocating causes with their sources.

A study conducted on food losses and the potential for reduction in Switzerland found that 48% of the total calories produced are lost across the whole food value chain. The study emphasized the need for solution to avoid food losses. However; the implementation of solution measures requires all "actors" to be involved, including the government [19]. Some of the defined causes for food losses are associated with poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, lack of access to markets and natural disasters [20]. Solutions that involve changing attitudes, behaviors, technologies, developing policies, strategies and initiatives to address the issues of food loss must be done in collaboration with the relevant stakeholders that influence decisions or are affected by decisions. The different aspects considered in the context of Food loss reduction are industrial, commercial, and institutional. Any solution will concern all the involved in processing, preparing, preserving, distributing, and serving or selling food products, governmental agencies with responsibilities related to food, environment, agriculture, public health and social development. Nongovernmental Organizations (NGOs) that work on food loss reduction, researchers; both within and outside of academia [21]. Post-harvest loss reduction was found to be associated with several issues that are considered locally and globally relevant to economic development and social welfare. Moreover, issues like food security, food safety, economic revenues, employment in the food sector, and climate footprint are relevant when considering solutions to the problem. Those issues were found to have a strengthening effect on the post-harvest management in general and positively support mobilizing resources for the target of post-harvest food loss reduction [22]. From the previous research, we conclude that the food loss reduction challenge expands vertically from local, regional, national and global levels. In addition, it expands widely horizontally over multiple sectors, institutions and stakeholders. The weight of the problem was proven to be heavy and costly. Conclusively, the problem is systemic, and any resolution requires analyzing the causes within the system and developing amendments to the system. Systems engineering is the discipline concerned with systems analysis and development. Material control falls in the core definition of the problem and the targeted change must be based on efficient and proper usage of that material and its applicability to food loss and food waste [23,24].

This study discusses food loss reduction in a farmed salmon post-harvest processing system in Norway from systems engineering perspectives, aiming to

1- Gain a wide-covering insight into salmon PHPS through systems engineering.
2- Identify the causative elements in material transformations within the PHPS.
3- Discuss how to cause the desired adaptation; food loss reduction? A scheme for change that serves to achieve target 12.3.

2. Methodology: Systems Engineering

Systems engineering is defined by the international Council on Systems Engineering (INCOSE) as a "transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles, concepts, scientific, technological, and management methods" [25]. Systems engineering is the discipline concerned with the system as a whole; it emphasizes its design, construction and operation considering economical structures, environment, technology, and its interactions with other systems [26].

The system's interacting functions and elements require a holistic evaluation of the variations in the system's structure [27]. Systems are a collection of hardware, software, people, facilities, and procedures organized to accomplish some common objectives that stakeholders of the system are interested in [28,29]. Systems engineering principles can guide toward understanding an industrial system and gain insight into its structure and behavior [30]. System engineering allows to address the system's interacting elements in relation to the targeted problem or quested development. The understanding of a comprehensive system requires: recognizing the multidisciplinary nature of the system's components, defining the stakeholders who contribute to the decisions that direct the system, and describing the system's behavioral dynamics. Analytical system understanding will help in problem formulation, revealing its causes, suggesting actionable measures, and the reassessment for the efficiency and consequences of the applied set of measures. In summary, a system engineering framework structured based on the three main concepts of requirements, behaviors, and structures [26] expected to result from the system functional configuration in Figure 2.

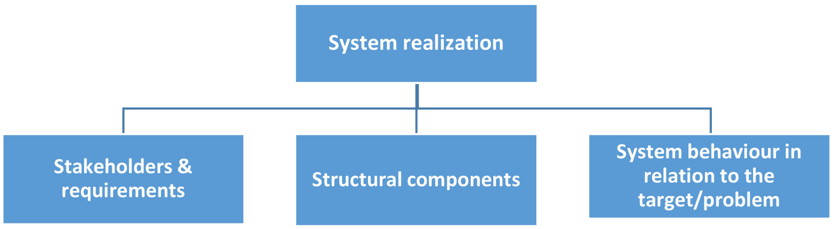

Figure 2. Conceptual map for a system understanding framework.

2.1. System's Stakeholders

When identifying the stakeholders of a system, those who maintain the system, are involved in its development, influenced by its outcomes and can influence the system's behavior are fundamental. Moreover, this is a vital step in approaching the targeted problem, the developmental quests, and eventually, reaching a functioning resolution. Any adjustment that aims to bring the system closer to the target must appeal to the interests and avoidances of the stakeholders. The stakeholders organize and carry out the maintenance, regulation and development of the system. The stakeholders are identified to be included and represented in the decision-making process that will formulate a solution for the problem; in this case, the food loss reduction target. Food production and food loss concern diverse groups and touch different interests. For this reason, a multi sectoral approach is needed to identify the stakeholders due to the wide civic engagement in directing and governing food systems, as it is a vitally impactful sector on society's health, economy, livelihood and welfare. Moreover, the food system is structured on sub systems and activities of multiple sectors such as agriculture plant production, animal production, post-harvest processing, food industry, food retail and services.

Defining the stakeholders in the development process of the food post-harvest industrial system within the context of Sustainable development goals (SDG) must reflect the inclusion of the three pillars of sustainability Environment, Economy and society as system requirements, starting from the innovation stage, as Figure 3 illustrates.

In addition, food systems and their impacts expand over multiple levels, including local, regional, national, international and global. The inclusion principle applies to stakeholders from multiple sectors and multiple levels of impact, ranging between local small pressure groups all the way to global United Nations institutions (Table 2).

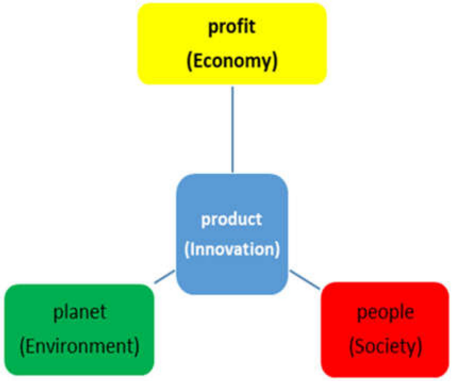

Figure 3. Sustainable Product innovation model published by Delft University of Technology and UNEP [31].

Table 2. Food systems stakeholders' interests and type of involvement.

Stakeholder	Interest	Involvement
Private sector	revenue	ownership and management
Academia	Science, development	research
Public health governance	Food safety, community nutrition	Inspection and guidance
Env. authorities	Environmental protection.	Inspection and guidance
Local NGOs	Social agenda	Info., Ethics, pressure groups.
Global institutions (UN/FAO)	SDG/2030 Agenda	contribute to info. /ideas

The inclusion concept translates, in practice, to communication with the Stakeholders, to identifying their requirements, interests and avoidances in relation to the addressed problem and targeted solution. Any suggested solution will have costs and benefits, consecutively, and it will face resistance by those who might bear cost or more responsibility with more chance to be embraced by the beneficiaries. The socio-economical context that PHPS are operating within imposes commitment for environmental protection and highlights the economical contributions of this sector in generating revenue and employment opportunities. A social agenda for relevant ethics and its associated regulations are critically vital elements of the system, for example, animal welfare, gender equality, child labor, GMOs and corporate social responsibility. Moreover, sustainability is becoming more of a social demand and a global mission.

2.2. Systems Structural Components

Partitioning the system into functional and physical building blocks is a means to configure the system's functions, manage its interfaces and develop its capabilities [26]. Each building block (structural component) corresponds to a body of knowledge that is tied to a discipline of science or a credible source of information. PHPS is structured on physical and functional components that serve the delivery of the designed product. PHPSs are composed of physical elements of material, machinery, labor, and energy. Functional components include procedures, quality standards, food safety systems, measures for compliance with environmental regulations, and legal restrictions. Physical and functional components work together to produce a food product fit for human consumption that can compete in the market. The components of the system studied and developed by various disciplines of science and management include Food technology, Human Nutrition, mechanical engineering, Industrial Hygiene, Industrial ecology, Quality assurance management, Production management, social sciences and Business administration. The targeted problem of food losses in a PHPS has several aspects not limited to the applied technical expertise and process management but also has to do with the commercial profit margins, legislations and social trends. The targeted problem needs to be addressed in an interdisciplinary manner to cover the environmental aspects, economics, social and cultural perspectives. Just as food science and technology is the discipline of science that is specialized in food products, qualities and processing, other disciplines of science cover the other concerns and aspects of the problem.

The system's complex dynamics can be understood further by deconstructing it to its basic components and associated body of knowledge (Table 3). Food losses are not only lost human nutrients but also lost natural resources and environmental stressors; they impact the climate with a higher carbon footprint, negatively affect biodiversity, cause more lost water, more stress on land use and surface water hypertrophy [32]. Food loss is a system performance indicator and a challenge for research and development. Any suggested solution needs to first review relevant legislations and social cultural acceptance. All these multidisciplinary perspectives of the problem of food loss flow through the system as information that decides the system's behavior.

Table 3. Structural components and associated disciplines of a post-harvest processing system (PHPS).

Element of the System	Associated Discipline
Human Food material	Food Technology + Human Nutrition
Product development (R&D)	Food Technology + Engineering
Quality criteria	Food Technology + Quality assurance management
Machinery and automated production	Mechanical Engineering
Food safety	Food Technology + (HACCP based systems)
Environmental impacts	Industrial Ecology + LCA + EMS (ISO 14001)
Costs and revenue	Business administration+ Marketing + industrial management
Social responsibility	Social science + Decision making framework+ diverse info. pool

2.3. System's Behavior

A system's behavior is the materialization of the assembled structural components, and a descriptive term for the outcome performance, results and choice of practices. A system's form and operations are based on numerous decisions made to insure the system's functionality [27]. A system's decisions are always based on information; the background collective knowledge that shapes the system, defines the flowing material and governs the system's actions (Figure 4).

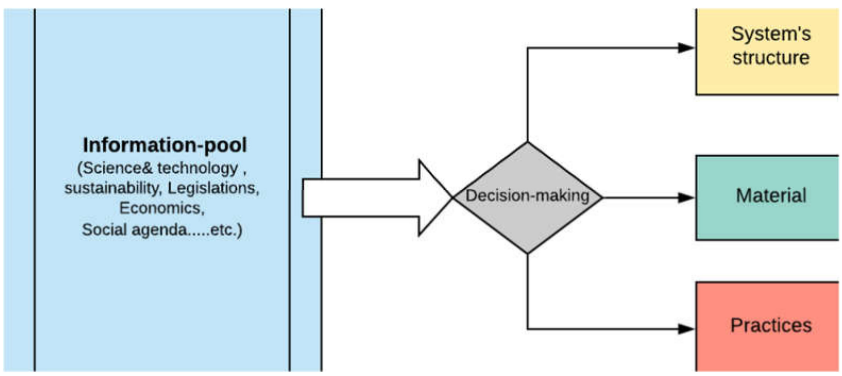

Figure 4. Information, terms and paradigms guide the system's behavior.

The information obtained from multiple disciplines lay the technical foundation that system processes are structured upon, including the terms and descriptions of the material processed by the system at the different stages of production. This material description determines the attitude of the system toward the processed input material and the output material in every process. The terms usually reflect the system's major interest or liability in association with material at each stage; weather it relates to cost, performance, quality, safety, or environmental impacts. Food losses are commonly described by the system as scrap, trimmings, non-edible parts, quality non-compliant, and that decides the following action taken by the system. Actions on material that cause food loss are usually regrading/downgrading that material, reprocessing it in limited cases, transferring it to a different processing system or discarding it. Material description or classification is based on measurements taken by the system for the purpose of control, either quantitative or qualitative. The decision maker support actions on material according to the paradigm of how to reduce, reuse or recycle. Materials that are not included by the product design cannot be reduced or reused in the same process; for example, peels off vegetables or guts, skin and bone from animal material. Consequently, these are dealt with as waste material, which is an environmental problem that requires a waste management solution.

3. Salmon Post-Harvest Processing System (System's Understanding)

System components: The post-harvest processing system is structured based on queued technical activities applied on the input material such as slaughtering, bleeding, cleaning, quality control, nutritional value measures, skinning, storage, deboning, and processing (Figure 5). In Norway, this industry is automated to an advanced level and has minimum dependence on human labor compared to fish processing systems anywhere else in the world. The system is supported by logistical activities: transporting, marketing, information and communication, administration and management. Processes include primary processing of slaughtering and de-gutting and secondary processing of filleting, fillet trimming, portioning, and producing different cuts like cutlets. Further processing might be applied in some factories and might include smoking, making ready meals or Packing with Modified Atmosphere (MAP). Products that have been secondarily processed are called value-added products (VAP). For the scope of this study, we focus on the Salmon fillet, as it is the major and final Salmon product.

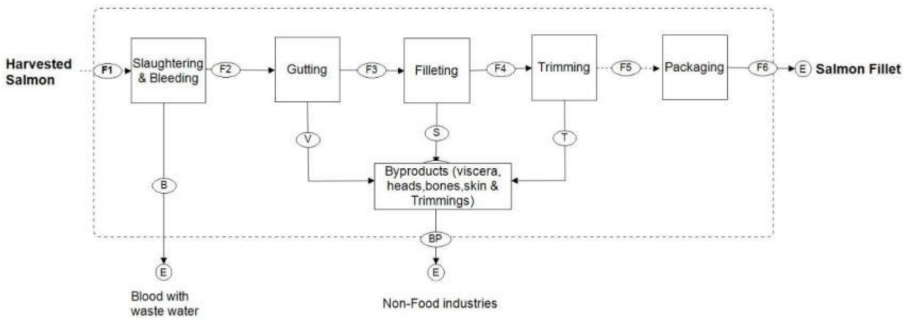

Figure 5. Salmon post-harvest processing system flow chart.

Stakeholders: (involved, affected socially, economically and environmentally) any outcome suggestions must consider their interests and avoidances. In the Norwegian context, it is important to highlight the clear harmonious flow of information and to share perspectives between the different stakeholders in a structured manner. This structured flow is very available in this case due to the fact that the farmed salmon industry in Norway encounters development challenges and limitations with Norwegian government-sponsored/led research and innovation endeavors [33,34]. The Norwegian government is committed to the Agenda 2030 Sustainable Development Goals, including food loss and food waste reduction targets [35]. Academic research in Norwegian universities and research institutions points to a trend in investigating the utilization of the harvested salmon biomass, optimum usage of the byproducts and the rest of the raw material [2,11,36,37].

System's behavior: The system's behavioral attitude toward the material is driven by product design. As the final product will be Salmon fillet, it considers the blood, head, skin, fins, bones and viscera as excluded material. During processing strict quality control, standards and food safety restrictions applied on the material, any material that is found to be not compliant for any reason will be excluded and marked out as scrap material (Figure 6). The salmon PHPS made a shift from being heavily manual labor-based to automation of the processing lines applying modern technology [38,39]. Automation increased the production rate and efficiency with the material, reducing the amount of scrap or delay-caused-spoilage. In the process of Salmon fillet production, the estimated ratio of the extracted marketable product compared to the input harvested biomass could reach 50% in most optimum conditions, leaving the other excluded 50% of the biomass out as a waste material that is being managed to eliminate its environmental consequences and slightly recover part of its costs. A fundamental question arises: why does this study see this excluded material of heads, skin, blood, viscera and trimmings as food being lost? The answer is because of its significant load of nutrients and its absence of any extraordinary hazards. These fish organs and remaining raw material are eaten by people in certain markets and culinary cultures [40].

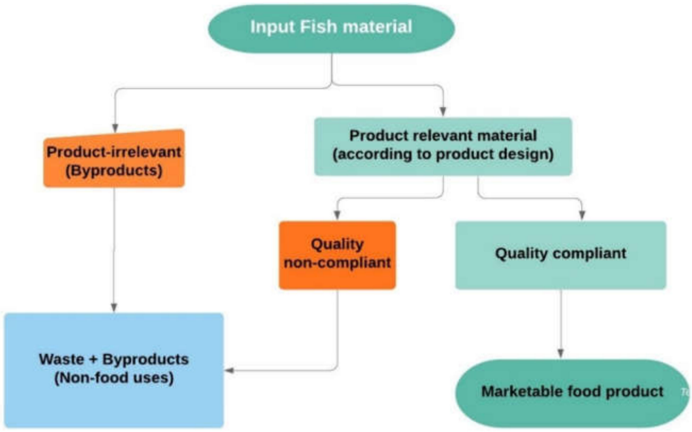

Figure 6. Salmon post-harvest processing system and basic material classification.

As the system operates under strict environmental regulations, proper waste management is necessary, due to the waste material being hydrolyzed and turned to silage that is transferred to non-food industries, including but not limited to the fur animals and pet feed industry to be used as a feed ingredient. Such a practice might somehow serve the concept of material circularity from economic and ecological perspectives. However, salmon is a resource-costly fish to grow in all aspects, and for pet feed, there are much less costly alternatives. Downgrading the salmon byproducts to become pets' feeding ingredients might involve taking part of this material far from its true potential as quality human food. Salmon biomass contains plenty of valuable nutrients, vital to human health in high concentrations like vitamins (B12, B3, B6 and D), essential fatty acids (Omega 3) and trace mineral (selenium, iodine, phosphorous) [41–43]. Those vital nutrients are not only present in the fillet product, they are also in the rest of the biomass that is turned to byproduct material. Targeting the post-harvest excluded material to restore those nutrients back to the human food chain will raise nutrients availability for the nutritional challenged global society [44] and conform to the UN Sustainable Development Goals 2 and 12.

4. Discussion: How to Achieve the Targeted Food Loss Reduction?

To serve the desired system's adaptation of less food loss, a change in the systems behavior and a paradigm shift are needed. Moreover, supportive data on quantities of lost food material are needed to highlight its nutritional content and reveal its human food potential. Awareness of this materials load of nutrients and the costly resources consumed to produce it will lead to a shift in the paradigm from describing the by-product biomass material as waste to as a secondary source. Secondary sources can become food ingredients in a new human food product. The nutritional content of secondary sources should be revealed and communicated to the concerned stakeholders as proof of its significant potential as a human food and a source for community nourishment. In addition, the monetary cost and the carbon footprint of the secondary output material both are measurable parameters that need to be highlighted and presented for the decision makers who are seeking to maximize the revenue and to minimize eco-impacts through the most feasible and efficient use of this worthy material. Research and development endeavor to develop new food products by turning all the remaining raw material to quality, marketable food products as a starting point. Alternative scenarios based on allocating responsibility of minimum food loss to the PHPS will demand a change from the current material downgrading measures toward a status of multiple production lines for diverse food products within the same factory. The advanced level of automation that Norwegian Salmon PHPSs have reached can potentially allow further processing of the remaining raw material to become food products without being labor shortage-limited or -dependent. Minimum waste production without shifting the responsibility for the material to another non-food system will guarantee a higher harvested biomass to food conversion ratio. Usually, the material that is classified as a production ingredient is handled with care; its cost and quality are controlled in a standardized manner. The inclusion of byproducts as human food ingredients is a necessary step to facilitate such a fundamental transition.

At the operational level, output waste material is classified either as non-compliant with quality control standards, or as not part of the final product design, commonly described as not edible or not marketable. However, it is possible to change that classification and its associated system's behavior by highlighting the nutritional content and potential revenue of this excluded material. The current practice of ensiling the salmon by-products (Enzymatic hydrolysis) lowers the proteins quality and quantity in the produced silage material [12,45]. Salmon proteins are very high-quality animal proteins and they are costly synthesized within the aquaculture production system. The ensiling process deconstructs material that was intentionally constructed by a previous anthropogenic system; a sign of contradictive work and a waste of resources. Data has supported the need for the system's decision makers to reconsider the material downgrading decision. The synergy between the salmon PHPS and non-food industries like the fur animals feed, fertilizers, or bioenergy industries must be questioned on the basis of prioritizing the conservation of nutrients within the human food chain. The use of salmon byproducts in the feed industry is a fit environmental circularity solution with economic benefit to reuse waste material instead of disposing of it. On the other hand, this by-product material carries a significant load of nutrients and the legislations do not prohibit its usage as human food if compliant to health restrictions, as with the rest of the fish anatomy. This dual fitness for food and feed brings a legitimate question of prioritizing. Recycling byproducts from the food process to the feed process out of the human food chain could appear as an easy waste management solution, but that does not serve the growing human population needs for food and nutrients. Thus, a regulated disengagement between the food and feed industries might be a reasonable idea and a legitimate suggestion. Achieving a salmon PHPS with minimum food loss is an added value that appeals to the interests of all the system's stakeholders (Table 2), starting with the private sector earning more revenue from costly raw material, gaining technological advancement of the industry and improving operational efficiency. The societal interests in food security, efficient utilization of natural resources and community nutrition would all benefit from turning the underutilized material of salmon byproducts into food. For the governmental stakeholder and the global stakeholder, who are both committed to the food loss reduction target, such a transition in a major commodity value chain would be a step closer toward achieving a set target.

5. Conclusions

A system's engineering approach to food loss reduction in farmed salmon PHPSs has provided a holistic understanding of the system and brought attention to a wide range of practicalities that need to be considered to reach the quested change. This study accomplished its objectives by developing insight into the salmon PHPS, identifying what drives the material transformations within the salmon

PHPS and discussing scenarios with required system adaptations to result in food loss reduction. This study stresses the need to prioritize keeping nutrients within the human food chain as a key concept in addressing this issue. Terms and classifications that define the processed material can embrace this perspective by defining the output material based on its nutritional content. This will reveal to the decision maker the true potential of the by-product material as food. The relationship between the PHPS and the preceding production systems, salmon feed and salmon aquaculture, should be considered to present the environmental and economic costs of this biomass to avoid its downgrading to non-food uses. The synergy with the feed industry and bioenergy industry needs to be reevaluated in the shadow of prioritizing human food needs. The main contribution of this study is the qualitative description of the system and the relevant concepts presented in addressing the food loss challenge. The main limitation of this study rises from the need for a quantitative description of the material flowing through the salmon PHPS. The exact quantity of the material being downgraded to non-food, its actual content of nutrients and monetary costs is a gap in the knowledge that this study did not fill. Based on that limitation, we suggest that further studies apply quantitative methods for a material inventory and analysis. The material flow analysis methodology could serve that purpose and overcome this limitation.

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Paper III

Food-Loss Control at the Macronutrient Level: Protein Inventory for the Norwegian Farmed Salmon Production System

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Food-Loss Control at the Macronutrient Level: Protein Inventory for the Norwegian Farmed Salmon Production System

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Abstract: The growing world population and the growing need for food are raising the importance of more efficient and sustainable food production systems. Food loss is a significant global challenge and a major stressor on natural resources. True assessment of food loss is a precursor to its reduction. This study aimed to assess the actual food loss in the Norwegian farmed salmon production system in the year 2019 by quantifying the protein flows and stocks in the system. Protein served as an indicator substance of the true systemic food loss. This study highlights the system's qualitative value-adding conversion of plant protein into higher quality marine animal protein, with deposited vital trace minerals harvested from the sea and carried to the human food chain. However, it takes a lot of protein from multiple sources to produce salmon. We found that the total invested feed protein is about four times more than the harvested salmon protein, and about 40% of that harvested protein in the salmon biomass departs the human food chain by flowing to other non-food industries. The current post-harvest practices, material trade-offs, and waste management solutions could be adjusted to a context that prioritizes human food security. An alternative scenario is presented in this study, based on a hypothetical new food product in parallel to the main salmon fillet product. The alternative scenario turned 99% of the harvested protein into food and adjusted the ratio between the invested marine protein and the human food product protein. The originality of this research is in its approach to food loss assessment at the industrial level by means of a systemic macronutrient (protein) inventory.

Keywords: responsible seafood producer; aquaculture; Atlantic salmon (*Salmo salar*); substance flow analysis (SFA)

1. Introduction

The Malthusian dilemma of a growing population versus the Earth's carrying capacity is gaining momentum [1,2]. In a reality where hunger and malnutrition are the biggest risks to health worldwide, affecting hundreds of millions of people [3], the total population of 7.7 billion in 2019 is expected to reach 9.7 billion in 2050 [4]. Hunger and malnutrition are consequences of unsustainable food systems [5]. The United Nations 2030 Agenda for Sustainable Development clearly pointed toward the global challenge of developing sustainable food systems with set goals to be pursued. Sustainable Development Goal (SDG) 2 raised the issues of hunger, malnutrition, food access, and affordability, while SDG 12 addressed responsible food production and consumption through reducing food loss (FL) and food waste (FW) [6]. The United Nations Food and Agriculture Organization (FAO) clearly defines the technical term FL as the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain before the retail stage. After it reaches retailers and consumers, it is described as FW [7,8]. A clear distinction in terminology draws borders of responsibility between industry versus retailers and producers versus consumers. FLs are taking place in various food supply chains at the different stages of production, post-harvest processing, and distribution. It is critical to assess the extent and causes of FL at the industrial level with consideration of the effectiveness and feasibility of its prevention and reduction measures. Developing appropriate strategies to reduce FL and FW is one of the most important issues in relation to sustainable development [9].

FL is causing major negative impacts on the environment, food security, and livelihoods of economically vulnerable people. Therefore, reducing FL to a minimum is vital for the sustainability of food supply chains. Reducing FL starts with the accurate assessment of the quantities of lost food [10]. For this purpose, assessments using qualitative and quantitative methods interactively have been developed and applied. The level of FL differs from one stage in the food supply chain to another, which raises the importance of an integrated, holistic approach to assess FL and to define its causes [11]. The various food production systems have different kinds of FL specific to the kind of harvested biomass, be it is plant crops, animals, dairy, fisheries, or aquaculture; therefore, methods need to be considerate of the technical specificities of production systems and processed materials. Food processing is the stage at which most FL is taking place, far more than the supporting logistical operations [12]. FL is commonly referred to as the decrease in the quantity of the "edible parts" of plants and animals that are produced or harvested for human consumption, but that are not ultimately consumed by people [13]. The description of edible parts is too supple, and is influenced by the product design, market preferences, culinary culture, processing costs, and revenue [14]. Post-harvest processing by-products are the subject of innovation and development for new food products in many different food value chains around the globe [15–20].

In this study, we approached FL in one of the global seafood supply chains with a tailored method for this purpose. The Norwegian farmed salmon industry is a globally high-profile seafood supplier, a significant economical contributor, and a steadily growing aquaculture producer [14,21,22]. Total global production of farmed Atlantic salmon in 2019 reached 2.6 million tons, 66% of which was produced in Norway [23]. Besides Norway, farmed Atlantic salmon is produced in Chile, Scotland, Canada, the Faroe Islands, and Sweden, and is just starting up in a few other countries. The major markets for farmed Atlantic salmon are Japan, the European Union, China, and North America.

Norway, the world's largest producer of Atlantic salmon, started salmon farming 50 years ago, persevering with work in research and development. The industry successfully achieved breakthroughs at all levels—i.e., technological, economic, and environmental. The research was fruitful in developing salmon feed, feed technology, aquaculture equipment, vaccines, and fish farming management methods [24].

The sustainability endeavor in the Norwegian farmed salmon industry is rising as a result of the government's regulated commitment [25], industrial interests, and perseverance in scientific research [26]. The main limitations and challenges facing the Norwegian salmon aquaculture are sea lice parasites [27] and fish escapees [28], for both ecological and operational reasons. The published scientific literature from Norwegian institutions and corporate sustainability reports reflects seeking sustainability for the salmon value chain in a holistic and inclusive manner [26,28–30]. The aspects of resource conservation, ecological impact, and climate change are frequently present in their measurable parameters. However, the FL issue is embodied in multiple contexts of material efficiency, feed raw material development, biological feed conversion rates, and the utilization of the rest of the raw material. Therefore, an FL assessment for the Norwegian farmed salmon supply chain is a fertile area for further investigation and for the introduction of approaches and methods developed for that purpose.

FL in fish value chains is a globally recognized significant target [8,21]. Achieving FL reduction requires qualitative decisions on which material is food and which is not as a starting point. This is justified by the fact that significant portions of harvested biomass are usually classified inedible or excluded as non-food material in different production systems for various reasons. Material within the food production systems, especially at post-harvest processing, is classified according to the design of the main product, the marketing desirability, the culinary culture, the quality control standards, and several other perspectives. To tackle this issue, we considered the material's nutrient content as the major criterion that is more objective in judging its potential and value as food. In fish value chains, the estimated weight of post-harvest processing by-products (heads, viscera, frames, skins, tails, fins, scales, blood, etc.) is between 50% and 70% of the whole fish [31], which is usually classified inedible.

Atlantic salmon (*Salmo salar*) can be described as nutrient-dense biomass that contains high-quality marine animal protein, Omega-3 fatty acids i.e., eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), vitamins (i.e., A, D, Niacin, and B12), and vital trace minerals (i.e., selenium, phosphorous, potassium, magnesium, zinc, iodine, and calcium) [32,33]. It is no wonder that salmon tissue carries all these trace minerals when grown in sea cages in a sea water medium. Salmon's desirable pink color comes from a pigment called astaxanthin, a natural antioxidant compound, with proven health benefits [34]. Protein is a structural macronutrient that is clustered with all of the other micronutrients that are vital for human nutrition [35]. The role of protein in nutrition as a provider for adequate amounts of necessary amino acids, as well as its quality, is determined by its content of amino acids. Salmon protein is a high-quality marine protein, containing all of the essential amino acids [36]. Protein is the major component of salmon feed pellets; however, salmon feed is made with a mixture of plant protein and marine fish protein. With research on and the development of salmon feed, the percentage of plant protein ingredients (mainly soy and other grains) is increasing, while the amount of marine protein is decreasing. The marine protein feed ingredient is harvested from multiple fish species (e.g., anchovies, herring, sardines, and blue whiting), and it is still a major component of salmon feed pellets [37,38].

Salmon in Norway are grown in sea cages, which is a system that has many advantages over land-based aquaculture. For instance, there is no need for water filtration and the sea water can contribute to the nourishment of salmon with its rich content of minerals and electrolytes. However, in repeated incidents, fish escape from sea cages to the surrounding environment. Furthermore, fish excretions mixed with the spilled feed sit at the bottom of the cage as a sludge material, which can cause environmental problems such as eutrophication [39]. To tackle this problem, experiments have been done using sludge for energy production (biogas) and fertilizers [40].

At the post-harvest processing stage, where the salmon fillet is the targeted main product, all the processing by-products are transferred to the ensiling process, an enzymatic hydrolysis in acidic conditions to break down the tissue, which limits the growth of spoilage bacteria. The ensiling process flows from the reception of the rest of the raw material, through the physical treatment (mincing/grinding), addition of acid, mixing, hydrolysis, and heat treatment, to oil recovery and storage. The resulting silage is a thick liquid that is used for several other purposes, such as fur animal feed [40,41].

The ensiling of salmon by-products reduces the overall quality of the material in general, thus losing all of its sensory and texture qualities as seafood. Moreover, the protein quality is severely reduced and might cause its total degradation to a non-protein nitrogen compound if the hydrolysis process is not stopped at the right time [41]. The estimated protein recovery after the hydrolysis process ranges between 47% and 70% of the starting protein content of salmon by-product material [42]. Earlier studies found that soluble and insoluble protein isolates from salmon head and viscera have potential as functional protein ingredients [43,44].

In general, there are proven huge potential benefits from the utilization of salmon aquaculture by-products, such as environmental, economic, and food security [45]. This potential needs to be explored and presented to the industry decision-makers and developers.

Applying the concept of defining salmon by-product materials by their nutrient load and not by market-based edibility classifications [14], in this study we chose protein as an indicator substance of actual FL. By assessing the amount of protein being lost from the human food chain, we can establish clear insight into the amount of real FL independent of main product design, market bias, or customary food perceptions.

The available information and measurements on Norwegian farmed Atlantic salmon (*Salmo salar*) anatomy, tissue chemical composition, feed protein content, and biological conversion rates were all employed in this study to account for the fractioning of the material and its protein load through all stages of production. Applying a protein inventory to the system can reveal the true nutrients cost of production and the potential value of salmon by-products as a food and a rich source of nutrients. The results are discussed to identify the reasons for FL and the possible measures for its reduction through a suggested alternative scenario.

This study aimed to contribute to the discussion on farmed salmon value chain sustainability and FL reduction by investigating the following:

(1) The quantities of input and output protein for every process.
(2) The potential of salmon by-products as food and the amount of protein that does not reach the human food chain.
(3) How the system's protein inventory can more accurately reflect the true FL and can assess the efficiency of biomass conversion into food.

2. Methods

For the purpose of establishing a protein inventory by mapping the protein flows and quantities in each process, we followed the basic procedures of the method of substance flow analysis with the adjustments highlighted and explained in the discussion

2.1. Substance Flow Analysis (SFA)

SFA is an analytical method of tracing and quantifying flows and stocks of a specific substance within a well identified system [46]. SFA can be effectively used to asses and support sustainable development of the industry [26,47]. It is a key tool for effective resource management, as well as for investigating and quantifying secondary or anthropogenic resource stocks [48].The SFA method includes the following basic steps: (1) Definition of research objective and selection of monitoring indicators; (2) system definition, including scope, boundaries, and time frame; (3) identification of relevant flows, processes, and stocks; (4) design of substance flow chart; (5) mass balancing; and (6) illustration and interpretation of results and conclusions [2,46,47]. This method facilitates the creation and comparison of alternative scenarios [49].

2.2. System Definition and Flow Description

The investigated system is the Norwegian farmed Atlantic salmon (*Salmo salar*) production system based on in the harvest of year 2019. It is structured on three subsystems, namely, feed production, aquaculture, and post-harvest processing [14], and is tailed by uses and waste management solutions of the rest of the raw material. This study defined FL assessment as a research objective and selected protein as an indicator substance. A mass balanced protein flow analysis model was developed based on the existing practices and technology. In the interpretation and discussion of the results, consideration was given to (1) the differences at the substance level between plant and animal protein; (2) the spatial and temporal variations between the three sub systems (i.e., feed production, aquaculture, and post-harvest processing); and (3) fish nitrogenous secretions are not considered protein in terms of the definition of substances, although they result from protein metabolism, an unavoidable biological process, so they were not included in the model.

2.3. Data Sources and Quantification Method

Quantification of the flows according to the rate of annual production, the chemical composition of the feed, the feed-to-fish conversion rate, and the post-harvest processing outcomes were fractioned according to the anatomy of Atlantic salmon and the protein content. The quantities of produced salmon were sourced from the National Statistical Institute of Norway (Sbb.no), the main producer of official statistics in Norway. The amount of salmon produced by Norwegian aquaculture in 2019 totaled 1,357,304 tons. The calculations were based on equations, ratios, and cofactors obtained from published articles of scientific research and industrial corporate reports from Norway. The quantity of salmon feed consumed in 2019 was 1,726,297 tons [50]. To calculate the amount of spilled feed (estimated to be 368,993 tons), we deducted the amount of eaten feed from the total consumed feed using the reported biological feed conversion ratio (Bio-FCR), estimated to be 1.0 (1 kg of feed to produce 1 kg of salmon) for eaten feed [51].

The feed protein content was 54.7%, split into 14.5% for marine protein and 40.2% for plant protein [51]. Escaped salmon from cages in 2019 reported by the Norwegian directorate of fisheries equaled 284,308 fish [52], with an assumed average weight of 2.7 kg per fish, totaling approximately 767.6 tons.

Atlantic salmon body parts, their weight fractions, and the protein content of each portion were used to calculate the quantities of protein in the post-harvest outputs and by-products (Table 1).

Table 1. Protein content in Atlantic salmon body parts *.

Salmon Parts	Weight Fraction	Protein %
Whole fish	100%	16.9%
Blood	2%	5%
Viscera	14%	10%
Head	10%	15%
Filleting byproducts (i.e., backbone, belly bones, back fin, collarbone, tailpiece, belly flap, pin bones, fins, belly membrane, and skin)	24%	~12%
Fillet trims	2%	17%
Salmon fillet	48%	19%

* Sources: [41,44,53–57].

By-product utilization technology reports on the quantity of farmed Salmon by-product utilization from the previous year (2018) mentioned that 90% of the material was used for other industries. The used by-products were divided as follows: 27% for biogas/energy, 24% for livestock fodder, 23% for fish feed, 17% for the pet food industry, 2% for fur animal feed, and 7% for miscellaneous uses [58,59]. There were no reports of change in by-product flows in 2019.

2.4. Variability Margins and Uncertainties

SFA models come with a level of uncertainty due to the variability of data sources [26]. We gathered the data and all information from Norway and salmon-specific reliable sources as an approach to minimize uncertainties. We applied the Hedbrant and Sörme method for determining uncertainty [60] by allocating the level of uncertainty to the reliability and accuracy of the information source. The equations used to construct this model were obtained from peer-reviewed published scientific research papers. Data on the production quantity of salmon were sourced from published official statistics collected on the local, regional, and national levels. With 95% probability, all sources of information in this study retained uncertainty levels of 0 and 1, as shown in Table 2.

Table 2. Uncertainty intervals and data sources.

Level of Uncertainty	Interval	Source(s) of Information	Example(s)
0	*/1	Official statistics	Norway salmon production in 2019
1	*/1.1	Official statistics on local, regional, and national levels; values in general (from the literature); and information from the industry	Byproduct uses, protein content in salmon body parts, and feed content
2	*/1.33	Official statistics at the regional and national levels, and values in general (for content)	Monthly feed consumption in each region
3	*/2	Monitored data	Nitrogen compounds from protein hydrolysis
4	*/4	Values in general for flows (from the literature)	Sludge in fish cages

*/1, */1.1, */1.33, */2, */4—uncertainty intervals

The intervals were inserted in the following equation to calculate the uncertainty factor:

$$F_{a.b} = 1 + [(F_a - 1)^2 + (F_b - 1)^2]^{0.5} \quad (1)$$

For example, the quantity of harvested salmon reported in the official statistics for 2019 was 1,357,304 tons (uncertainty interval*/1). The protein content in Atlantic salmon whole fish is 0.169 of its whole weight, as per the literature (uncertainty interval*/1.1). The calculated total harvested protein equaled 229,384.376 tons.

$$1 + [(1 - 1)2 + (1.1 - 1)2]^{0.5} = 1.1 \quad (2)$$

Therefore, the amount of harvested salmon protein in 2019 was very likely between 252,322.80 and 208,531.25 tons.

Another example of calculating the quantity of protein in the total harvested salmon viscera = harvested salmon × weight fraction × protein content:

$$1{,}357{,}304 \text{ tons} \times 0.14 \times 0.1 = 19{,}002.256 \text{ tons} \quad (3)$$

with the calculated uncertainty interval of:

$$1 + [(1 - 1)2 + (1.1 - 1)2 + (1.1 - 1)2]^{0.5} = 1.14 \quad (4)$$

Therefore, the value likely falls between 16,668.646 tons and a maximum of 21,662.572 tons, with an average value of 20,332.414.

3. Results

3.1. Current Practices and Flows

A map for the farmed salmon production system with all protein flows according to current practices is shown in Figure 1. The quantities of protein are indicated in Table 3 for each flow.

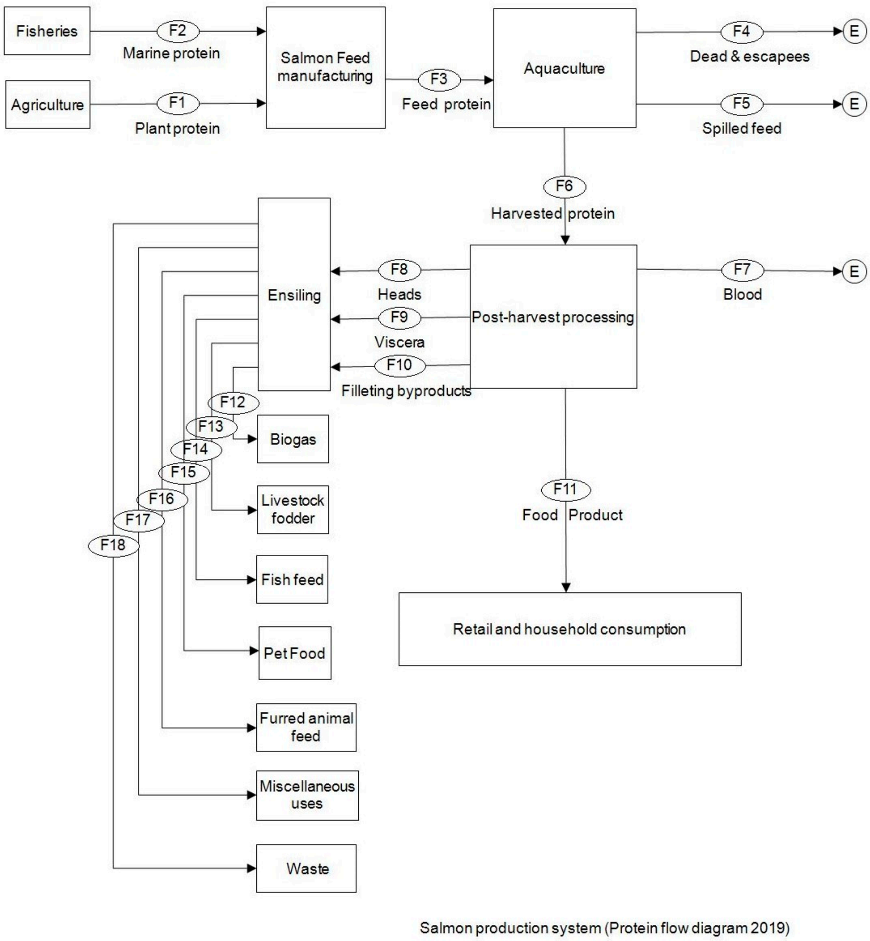

Figure 1. Processes and flows map.

Table 3. Calculated annual protein flows in 2019 *.

The Flows		Protein in Tons *		
Flow	**Description**	**Minimum**	**Average**	**Maximum**
F1	Plant protein feed ingredient	630,883.085	697,125.81	763,368.533
F2	Marine protein feed ingredient	227,557.332	250,313.065	275,344.372
F3	Feed pellets' total protein content	847,454.891	936,437.655	1,025,420.418
F4	Dead/escaped salmon protein	114.03	131.12	148.2
F5	Spilled feed protein	174,786.16	200,969.13	227,152.1
F6	Harvested salmon protein (whole fish)	208,531.25	230,427.025	252,322.80
F7	Blood content of protein	1190.617	1368.972	1547.326
F8	Head	16,866.67	19,393.29	21,919.92
F9	Viscera	16,668.646	20,332.414	21,662.572

Table 3. *Cont.*

The Flows		Protein in Tons *		
Flow	**Description**	**Minimum**	**Average**	**Maximum**
F10	Filleting byproducts and trims (backbone, belly bones, back fin, collarbone, tailpiece, belly flap, pin bones, fins, tissues, belly membrane, and skin)	38,337.885	44,080.9	49,823.915
F11	Food product for the market	108,584.32	124,850.25	141,116.182
F12	Silage for biogas	17,737.69	20,394.8	23,051.91
F13	Silage for livestock fodder	15,766.84	18,128.71	20,490.58
F14	Silage for fish feed	15,109.89	17,373.35	19,636.81
F15	Silage for pet feed	11,168.18	12,841.17	14,514.16
F16	Silage for furred animals feed	1313.90	1510.73	1707.55
F17	Silage for miscellaneous uses	4598.66	5287.54	5976.42
F18	Waste from silage	7299.46	8392.91	9486.37

* See text for details on calculating the uncertainty intervals.

Comparisons were made between the different flows and the quantities of protein, illustrated in Figures 2–4.

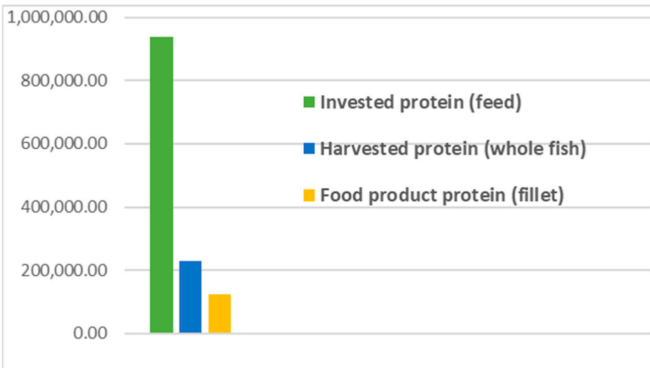

Figure 2. Quantity comparison.

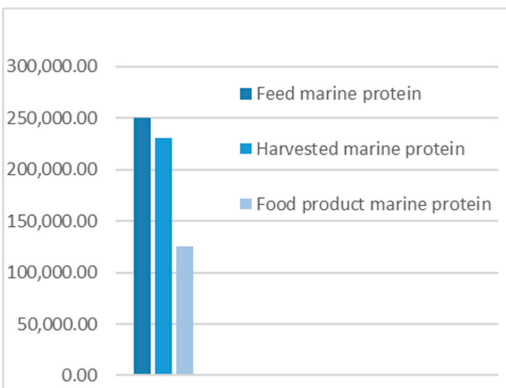

Figure 3. Marine animal protein quantities.

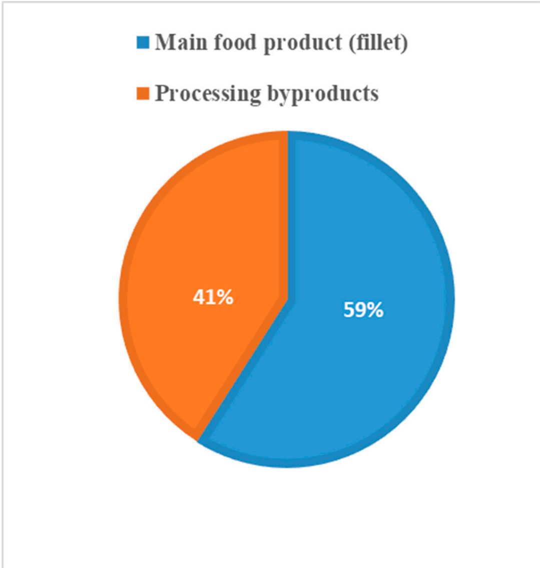

Figure 4. Post-harvest protein distribution.

3.2. Alternative Scenario

An alternative scenario was developed on the basis of conserving the harvested salmon protein and its holding biomass into the human food chain. This scenario limits all post-harvest flows into food production (Figure 5), presenting a need for a parallel food product B to be developed. Material trade-offs with pet food and biogas industries still exist, but in a different sequence. The change in the protein quantities in different flows suggested by this scenario illustrated in Figures 6 and 7.

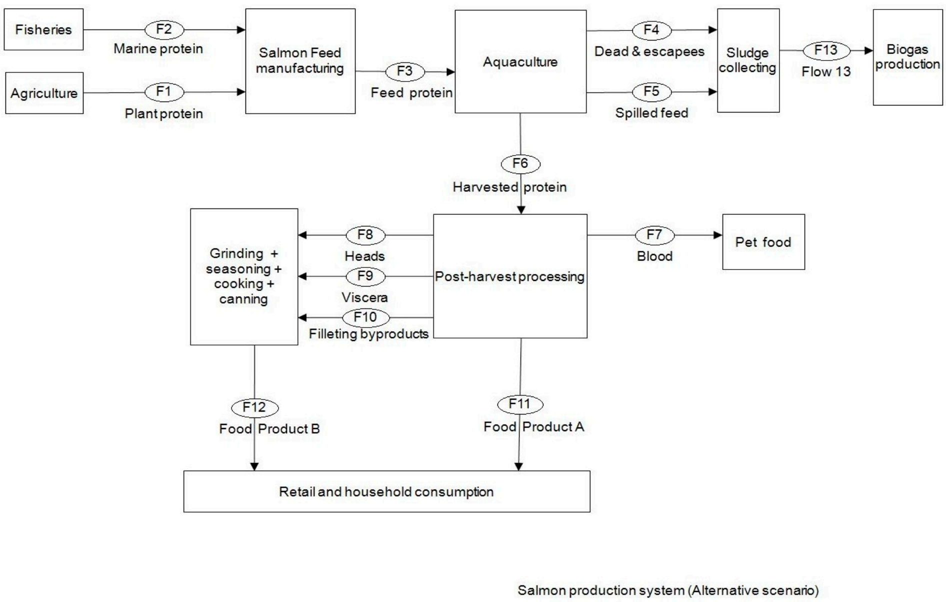

Figure 5. Alternative scenario.

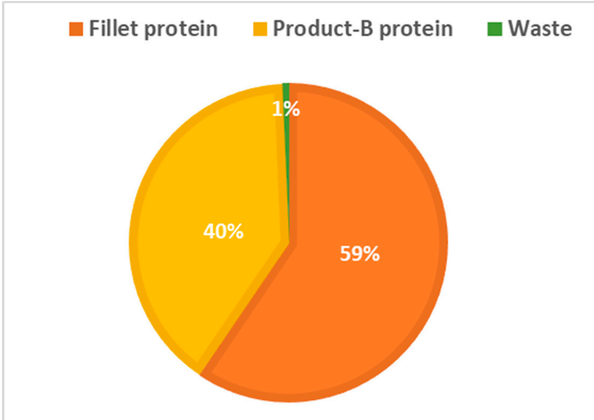

Figure 6. Alternative scenario post-harvest protein distribution.

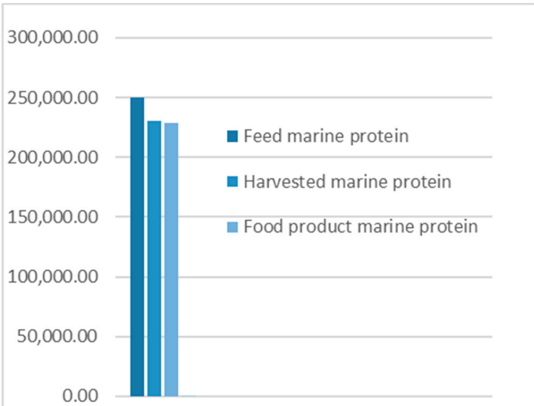

Figure 7. Alternative scenario marine protein quantities.

4. Discussion

- **The results** from applying protein SFA provided a clear picture about the system and the material. The total harvested salmon protein equaled less than 25% of the invested feed protein (Figure 2). The marine protein ingredient of the feed pellets equaled 10% more than the total harvested salmon protein (Figure 3). Approximately 41% of the total harvested salmon protein departed the human food chain for good as silage used for other industries (Figure 4). The estimated 85 kilotons of protein that turned into silage was embodied in approximately 650 kilotons of biomass. The quantity of protein in the model can reflect how nutrient-costly it is to produce salmon and how much of that salmon biomass is being lost during post-harvest processing.
- **The method** of SFA modeling of the quantity of protein flowing through the farmed salmon value chain served the objectives of FL assessment and reduction. Targeting protein, a biomolecule and a macronutrient, as an indicator substance provided a qualitative description of the material based on its optimum nutritional potential before the protein is broken down into other substances and nitrogen compounds. The method of substance flow analysis provided guidance on how to model a system and to quantify the flows and stocks of the traced substance; however, achieving the concept of 100% mass balance was not possible due to the complexity of biological processes and how the protein passes through fish metabolism, after which part of it is secreted as nitrogen compounds in feces and urine or breaks down during ensiling hydrolysis.

- **Uncertainties** of the SFA model result from seasonal and geographical variations, as this study included the three interlinked subsystems that structure this production system, and each subsystem has a level of independence, is geographically distant, and has operational needs and circumstances. We acknowledge the ambiguity due to variations in the size of the escaped fish, the number of dead and escapee fish, the amount of spilled feed, the seasonal variations in salmon physiology, and the percentage of protein content in the tissue. The available information and data covered most of the system and processes, with the exception of the miscellaneous uses of the silage (flow number 17). The reason for such a hazy description is that there are several experimental uses that are still under development.
- **The alternative scenario** in Section 3.2 (Figure 5) is based on further processing of the by-product material to re-introduce it as a marketable, quality food product that contains approximately 40% of the post-harvest protein (Figure 6). That will improve the system's efficiency and bring more balance between invested and harvested marine protein (Figure 7) with increase in the protein quantity that becomes available for human consumers. In this alternative scenario, we highlighted the desirable impact of developing a new food product to be produced in parallel to salmon fillets, in a clear invitation to food scientists and product developers. The invested marine protein ingredient in salmon feed usually comes from anchovies and sardines, two fish species that are typically food-processed for canning. Creating a canned food product from the rest of the raw material of salmon provides a nutrient-dense, affordable sea food product with a long shelf life and that is ready to eat. Such a product would be a valuable compensation for the marine protein consumed as salmon feed. With the right recipe and a good marketing plan, the monetary revenue from turning the down-graded raw material remains to an affordable nutrient-dense seafood product would be substantial. This scenario, if materialized, would put an extra 650 kilotons of seafood on the global food table. The most significant limitation of this scenario is the quality status of the salmon by-products upon delivery for processing and their fitness for food ingredients. For this scenario to emerge and function, by-products need to reach the processing line with acceptable microbial load and free from spoilage. This raises the importance of localizing responsibility over salmon by-products on the same post-harvest processing facility for quick processing and for ensuring the freshness of the material, preceding microbial growth and rancidity. In this scenario, both the salmon fillet product and the hypothetical product B must come out of the same factory.
- **Other scenarios** based on dry matter extraction of protein and fat out of salmon by-products could be suggested. Macronutrient recovery from by-products would have a positive effect on the system's efficiency and FL reduction "if" the recovered protein and fat were used as food. However, the total utilized biomass would be much less in comparison to the quantity in the first alternative scenario suggested by this study. Nutrient recovery requires further processing, associated with more production complications and costs. The main concept of this study was to consider macronutrients as indicators of the food material, not as a distinct target from the rest of the biomass. Our targeted FL reduction would be achieved if we were to manage to turn the whole 650 kilotons of salmon by-products into a food product, including but not limited to their 85-kiloton protein content.

5. Concluding Remarks

A system's protein inventory can serve as a sustainability evaluation criterion for food production systems. It takes a lot of food/nutrients to produce a more expensive food like salmon. Sustainable and responsible seafood production demands seeking the optimum status of zero FL. The maximum utilization of harvested salmon biomass within the human food chain needs to be prioritized over any other non-food uses. The quantity of hidden FL in the farmed salmon production system is significant; thus, new food products need to be developed using salmon by-products as their main ingredient.

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Paper IV

Systemic Insights on the Integration of UN Sustainable Development Goals within the Norwegian Salmon Value Chain.

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Systemic Insights on the Integration of UN Sustainable Development Goals within the Norwegian Salmon Value Chain

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Abstract: This study proposes a conceptual framework that aims to gain insight into the integration of the sustainable development goals (SDG) within the Norwegian salmon value chain (NSVC). The proposed framework was developed by applying the systems engineering six-step method and validated through empirical findings from the NSVC. The framework's application highlighted and analyzed the presence of the SDGs in corporate sustainability reports, academic curriculum, research, and governmental policies. This study uncovered the complexity-reduction elements within the system that drive SDG integration and assure their progress. The SDGs provide a global context for sustainability endeavors in the NSVC. A globally expanded value chain has an organic relationship with global sustainability terms and schemes. The existing practice of corporate sustainability annual reporting was found to be a significant channel for SDG communication. The novelty of this study was that it proposed a mind-map to understand SDG integration within an industrial value chain abstracted into three concepts: commitment, communication, and performance measurability.

Keywords: systems; sustainability; aquaculture; salmon

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1. Introduction

Sustainable development can be seen as an anthropocentric view of the inter-relationships between environmental and socio-economic issues [1]. On its seventieth anniversary in September 2015, the United Nations (UN) general assembly adopted the resolution, "Transforming our world: the 2030 Agenda for Sustainable Development". With its 17 sustainable development goals (SDG) and 169 targets, Agenda 2030 presented a plan to achieve a vision of a peaceful world free from hunger, poverty, and environmental deterioration, a world of prosperity and the efficient use of natural resources for all [2]. Agenda 2030 is a call for partnership, solidarity, and mobilization of all efforts at all levels [3]. In July 2017, the UN general assembly added a total of 231 measurable indicators under the SDG framework, introducing a layer of complexity of SDG interactions that needs to be unraveled to optimize the benefits of their implementation [4]. There is a consensus among governments, experts, and researchers that a localization process is necessary to realize the SDGs at the level of locally and regionally driven operations [5]. The 2030 Agenda emphasized the need for inclusive participation and stakeholder engagement for the successful implementation of the goals. Nonetheless, the SDG framework is perceived as a top-down approach and criticized for an insufficient focus on systems stakeholders' perspectives and the potential role of businesses [6]. SDG achievement depends on the integration of SDGs into local business practices, created policies, internal education, active management, and engagement in partnerships [7]. Moreover, SDG integration in corporate culture is associated with a paradigm shift toward shared values of a sustainable future, as demonstrated by the SDGs [6]. Businesses can derive clear objectives from the SDG global priorities, aligned with governmental policies, societal interests, and appeal for private sector investors [8]. The formation of multi-stakeholder partnerships for SDG implementation is an opportunity that benefits both governmental and non-governmental actors [9].

Education is placed at the heart of Agenda 2030 and SDG implementation and educating business leaders and society about the goals of the agenda is a necessary precursor for local integration [10]. Universities have the capacity to lead the cross-sectoral integration of the SDG, not only by educating the professional work force in the targeted sectors, but also by initiating cross sectoral communication among the different stakeholders and providing research-based contributions [11]. In local contexts, the implementation and monitoring must be operationalized within the national, sub-national, and local structures, processes, and practices [12]. While many firms and corporations around the world are struggling to develop a definition of sustainability and its associated requirements to both guide and scope their efforts, the SDGs provide a guiding vision to achieve sustainability as a result of collective international endeavors [13]. The SDGs are creating a platform for a systemic sustainability transition and providing relatively well-defined terms for relevant communications. Successful implementation of the SDG targets is seen as a promising way forward to achieve global sustainability [14]. SDG achievement requires a shift in mindset from transition to transformation in research, innovation, technology, and policy [15]. The integration of the SDGs within a system is a powerful catalyst for the system's development and increased efficiency [16,17]. There is a proven correlation between SDG integration and communication maturity [7]. SDG fulfillment depends on their reflection in the knowledge systems used to develop mission statements, action plans, corporate reports, and other business tools [18]. One of the main challenges facing SDG implementation is the limited availability of the relevant performance data due to a delay in quantifying and monitoring SDG indicators [19].

Systems engineering (SE) is defined as a methodical, multi-disciplinary approach for the design, realization, technical management, operation, and retirement of a system [20]. SE is a discipline of knowledge that can help businesses to provide significant social, environmental, and economical global benefits by turning the policy intentions into requirements for consistent delivery through enterprises and practical systems [21]. SE has been an active supporting discipline for the implementation of the SDGs through providing effective approaches and toolsets to reframe the SDGs [22]. The International Council on Systems Engineering (INCOSE) introduced its Vision 2025 for Systems Engineering, in which they promote the role of systems engineers in approaching the world's complicated challenges of sustainability and the growing stress on natural resources. Vision 2025 resulted from multidisciplinary work by leaders from industry, academia, and government. Vision 2025 reaffirmed the SE concepts of a multidisciplinary approach and stakeholders' expectations as a driver for a system's transition, a product's full life-cycle management, and data management [23].

Norwegian salmon value chain (NSVC). For several years Norway has been the world's second-largest seafood exporter. Seafood is the second-largest export product category in the Norwegian economy [24]. In Norway, the salmon industry is widely perceived as an economic success story [25,26]. Seafood value chains are not limited to the entities or activities of wild fisheries, aquaculture, and seafood processing, but also encompass and influence other industries [27]. The Norwegian salmon value chain includes aquaculture production, the salmon-feed industry, and postharvest processing [28]. Farmed Atlantic salmon (Salmo salar) in Norway is a significant contributor to the Norwegian economy and in 2019 it recorded a total revenue of about seven billion USD [29]. The world's largest salmon producers are Norwegian [30]. NSVC earns most of its revenue by exporting more than 90% of its production. The salmon industry in Norway employs thousands of people, and the numbers continue to increase [31]. NSVC represents all the activities necessary to transform primary input raw material into the output food product. The central activity of growing the salmon takes place in sea-cages at farming sites in the Norwegian marine environment. The salmon-feed industry is an important part of the NSVC; the feed is made using imported ingredients mainly from South America [32]. The salmon product is exported to the global market, including Japan, China, Europe, the Middle East, North America, and more. Because the NSVC imports raw feed ingredients from several countries and most of the final product is exported to countries all over the world, the NSVC can be described as a global value chain. The major sustainability challenges facing the NSVC, as frequently reported in the literature, are the following: sea lice parasites [33], fish escapees from the sea-cages in the farming sites to the surrounding marine environment [34,35], and the environmental footprint of the imported feed ingredients [36–40]. The efficiency in nutrient utilization management, starting from feed production all the way to postharvest byproducts, receives steady focus in NSVC sustainable development research [32,41–43].

This study's main purpose is to develop a systems engineering-based framework for gaining insight into the SDG integration process within the Norwegian salmon value chain. The proposed framework will be applied and its outcomes will be discussed.

2. Methods

2.1. Framework Development

The SE approach for developing a framework for the purpose of gaining insight on SDG integration within the NSVC in this study was guided by the rationale sequence of the six-step SE method [44–46], summarized in Figure 1. The six-step method starts by 1—identifying needs, based upon a stakeholder analysis; 2—defining requirements, based on needs; 3—specifying performance, system activities, and progress indicators; 4—analyzing the gathered information to conceptualize a model for the drivers of the performance; 5—designing, solving, and improving; 6—verifying, testing, and implementing.

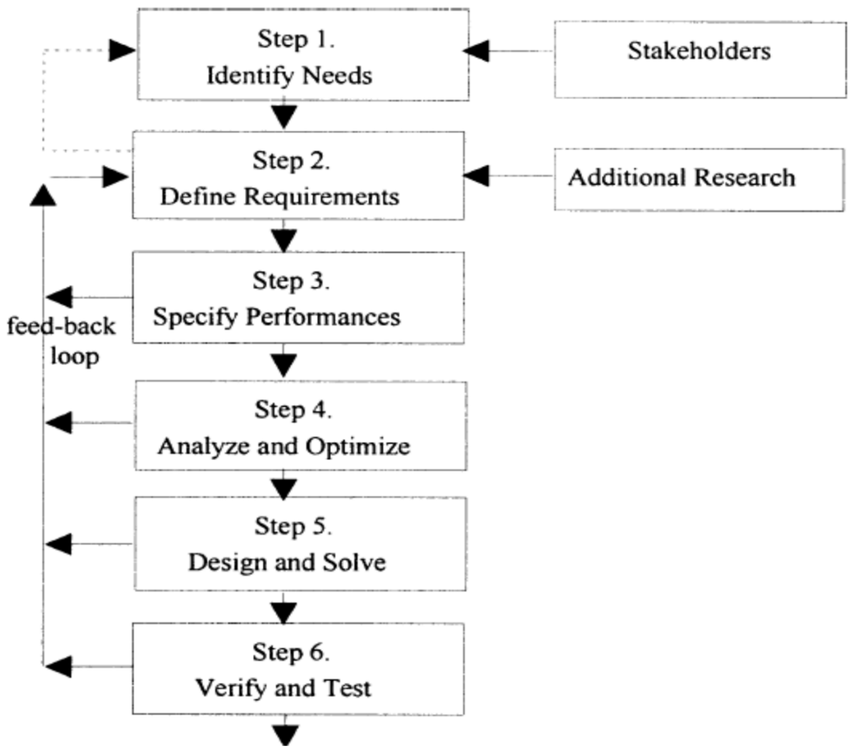

Figure 1. The systems engineering six steps method [47].

Step 1: Identify the needs.

What are the endeavors and resources being deployed by the NSVC stakeholders to allow SDG integration into the system's culture and practices? We need to know in which form the SDGs will materialize in the industrial operational structure.

In this study, SDG integration in an industrial value chain is understood according to how far the concepts and values of the SDGs are conveyed to the value chains as functioning mechanisms for change. The SDG framework was preceded by the Agenda 2030 declaration and followed by the global indicators framework. In logical order, it started with obtaining world governments' commitment, followed by releasing the SDG framework that stressed the importance of creating partnerships through efficient and transparent communication, specified in SDG 17. Later, the global indicator framework was announced, as a support for the implementation through the concept of performance measurement. Derived from the given logical order, the framework is based on commitment, communication, and performance measurability as core concepts to include in the framework. The defined key concepts in the UN SDG framework (summarized in Table 1) should be interweaved with SE principles. UN Agenda 2030 started with the announced commitment from governments on behalf of the people they represent and serve. Achieving the SDG requires strategic commitment from all stakeholders [48]. Commitment to the SDG is a value that flows top-down through the system. The SDG framework clearly states that multi-stakeholder partnerships and voluntary commitments (SDG number 17) are musts for SDG achievement. The global indicator framework for measuring the performance of SDG implementation was developed for performance measurement in achieving the SDG goals [14,49]. Communication plays a central role in almost every aspect of effective partnership to achieve the SDGs. Partnerships between stakeholders from all interests, scales, sectors, and organizational cultures require forming a shared understanding to think creatively and ambitiously about possible solutions. Within an industrial value chain, sharing information between functions provides adequate visibility and enables the making of good decisions [50]. Reaching an advanced level of goal-oriented functioning requires effective, transparent, and sufficient communication. The flow of SDG-relevant information through the system will be in multiple forms of communication, which will be unique to each partnership [51]. Business organizations reporting on the SDGs can support the planning, implementation, measurement, and communication of their efforts to achieve the SDGs [52]. The practice of corporate sustainability reporting can raise the level of transparency in communication about companies' activities, enhance stakeholders' confidence, and serve the SDG implementation and performance measurement [51,53]. The importance of communication about SDGs among all the stakeholders was frequently highlighted in the relevant UN literature and official statements. UN Secretary-General Ban Ki-Moon in 2015 said: "Business is a vital partner in achieving the SDG, companies can contribute through their core activities, and we ask companies everywhere to assess their impact, set ambitious goals and communicate transparently about the results".

Table 1. Concepts from the UN Agenda 2030 and SDG framework.

Source	Core Concept	References
Agenda 2030	Announced commitment.	[54]
SDG 17	Stakeholders engagement, partnerships. Voluntary commitment. Efficient communication.	[48,55]
Global indicator framework	Measurability of performance. Data collection and management.	[49,56]

The system's stakeholders are government (central government and authorities), academia (education and research institutions), and industry (private sector). These stakeholders have been identified based on their significant roles and proven involvement in the SDG integration process.

Step 2: Define requirements.

To gain insight on the inclusion of SDGs as a vision, goals, and targets in value chains, the needs must be established as requirements in the developed framework. The needs are from step 1: declared commitment from all involved stakeholders, communication about the SDGs within the NSVC, and measuring the performance of its application. The concept of performance measurability, with its associated data collection, is applied in companies as key performance indicators (KPIs). It provides businesses with a means of measuring progress toward achieving set objectives. The integration of SDGs within the operational structure of a value chain should begin with identifying the data for performance monitoring in accordance with the global indicators associated with the respective SDG. Environmental impact assessment methods and sustainability performance assessment methods that already are commonly applied have high relevance to SDGs, with growing levels of integration between these methods and SDG-required measurements [51]. Industrial systems are required to be flexible and adaptable to change, a capacity that is determined by their level of structural and operational complexity [52]. A complex system would react to any change in its static structure with unpredictable, counterintuitive behavioral dynamics [53]. Complexity mitigation requires consistent, clear communication and strong stakeholder engagement [54]. SDG integration carries substantial changes in the system that will face points of resistance versus drives and stimulants. For the developed framework to address SDG integration objectively, it must investigate the complexity level in the system. In Table 2, we present needs and requirements as SE concepts and terms.

Table 2. SE concepts [23,57] as required criteria in the developed framework.

Systems Engineering Concepts	Criteria for Framework Development
Problem-oriented	Insight on SDG integration into the NSVC
Product life cycle	Whole value chain as one system
Stakeholder engagement	Voluntary commitments, SDG communication
Complexity analysis	Response of system's structure to SDG insertion
Data management and reasoning	Performance measurability, SDGs as corporate KPIs
Validation	Supported by empirical findings.

Step 3: Specify performance.

The main consideration in this step is to specify how the SDG integration process will flow and how it will be carried out by the involved parties. From previous steps, a conceptual model for the SDG integration process evolved from the needs, requirements, and systems stakeholders (see Figure 2). The developed framework must be:

1. Representative of reality, reflecting the SDG integration process as carried out by involved stakeholders in a logical sequence and with respect to the timeline of events.
2. Evidence-based, describing the appearance of the SDGs in official communications, documents, and declared policies.
3. Capable of including the NSVC as a whole system, presenting highlighted barrier factors and support factors.

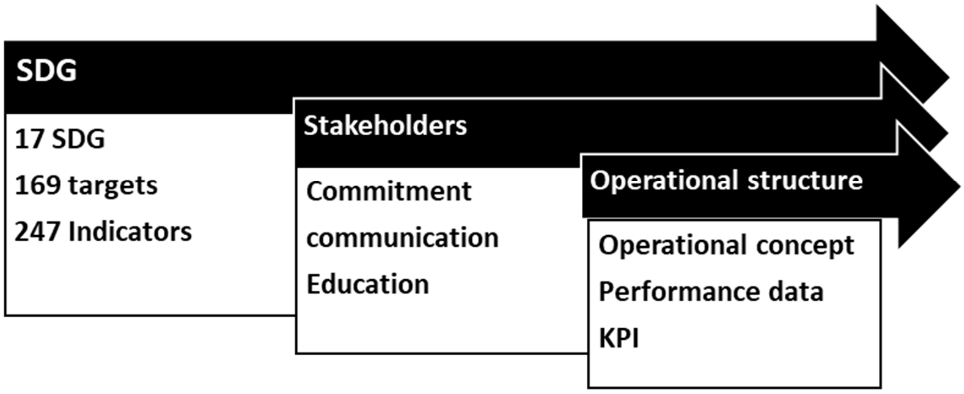

Figure 2. Conceptual scheme for SDG integration into value chains.

Step 4: Analyze and Optimize.

To analyze the outcomes of steps 1–3, we looked at the NSVC system, including its subsystems. The SDG integration process is a top-down approach that starts with commitment and relies on knowledge, education, and communication flow among stakeholders. Therefore, seeking evidence to validate the framework can be achieved by reviewing the sustainability reports coming out of the industry. In this step, we aim to define which factors drive SDG integration within the NSVC. Reviewing the empirical findings on the SDGs in Norway and in the NSVC can define insight factors that can drive the merge between the SDGs and NSVC or other factors that will add to the complexity of this integration.

Step 5: Design and Solve.

This step aimed to design a framework solution that can allow for gaining holistic multi-stakeholders insight. Elements defined in the previous steps were deployed in a conceptual structure (see Table 3).

Table 3. Summary of the conceptual variables as elaborated by the authors.

Variables	Reasoning
Commitment	Agenda 2030: Top governmental commitment. SDG: Voluntary stakeholders' commitment.
Complexity	Obstacles, incentives, and enablers for the integration of a global agenda.
Communication	SDG 17: Creating partnerships through communication. Flow of information to support the system and SDG integration.
System's Data	System's ability to measure performance in relation to SDGs and provide supporting data.
Sustainability KPI	Optimum form of a goal's integration in a company's strategy.

The proposed framework is composed of five steps, summed in the acronym (TCSAS) (see Figure 3), to be applied on the value chain as a targeted system. **First step**: Review the status of the existing commitments to the SDGs by the system's stakeholders. It is important to identify where the system is located, between governmental commitment to the SDGs and the voluntary commitment by academia and industrial sectors. **Second step**: A complexity analysis of the system to define obstacles and drives for SDG integration. The system's complexity will be approached by reviewing the system's three dimensions: structure, dynamic (operations), and sociopolitical [58,59]. **Third step**: Identify the system's communication channels between the stakeholders and the operational structure (company/corporation). Highlight the presence of the SDG in stakeholders' communications and in the operational responding communications. **Fourth step**: Align the system's existing data pool with the SDG and its associated global indicators framework. Identify existing data that serves SDG indicators and the needed measurable parameters to reflect the system's SDG progress track. **Fifth step**: How SDGs are being adopted as key performance indicators within the culture and practice of the company. Sustainability KPIs must be fit for corporate reporting and public communication on SDGs, rising from a supportive body of knowledge and cutting-edge scientific findings.

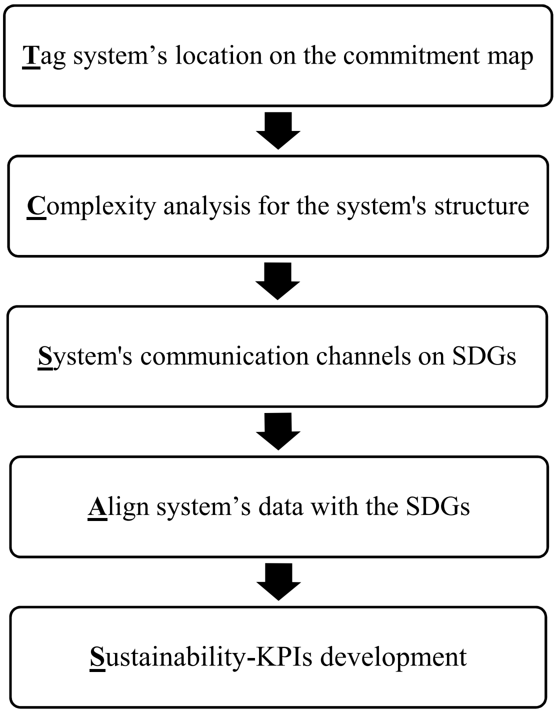

Figure 3. Framework to gain insight on SDG integration into value chains (TCSAS).

Step 6: Verify and Test.

We applied each step of the TCSAS framework on the NSVC and matched the concepts with the relevant empirical findings obtained on the SDGs from stakeholders' communications (Section 2.3).

2.2. Empirical Findings Acquisition

An empirical study was conducted on the basis of a critical discourse analysis (CDA) [60] of publicly available reports from the NSVC's stakeholders—government, academia, and industry—in relation to the SDG between 2016 and 2020. Governmental documents, corporate reports, published articles, and official websites (Table 4) were selected as units of analysis. The choice of units of analysis was based on common criteria, which included:

- The presence of SDGs in the system's communications.
- Statements of commitment to SDG implementation.
- Data-supported indicators on performance related to SDGs.

Table 4. Selected NSVC stakeholders for the scope of this study.

	Stakeholders	Empirical Findings on SDG
Government	Top Government	Commitment: 2021 voluntary national review [61]
	Ministry of Foreign Affairs	Follow-up Agenda 2030 report [61]
	Seafood Norway (national association)	Aquaculture 2030 report [62]
Industry	Lerøy Seafood Group	Annual sustainability report [63]
	MOWI	Annual sustainability report [64]
	Grieg Seafood	Annual sustainability report [65]
	Nova Sea	Annual sustainability report [66]
	SALMAR	Annual sustainability report [67]
	Cargill Aqua Nutrition	Annual sustainability report [68]
	BIOMAR	Annual sustainability report [69]
	Cermaq	Sustainability web page [70]
	Skretting	Annual sustainability report [71]
Academia	NTNU (Norwegian University of Science and Technology)	SDG education and research [72]
	UIB (University of Bergen)	Official SDG 14 (Life below water) hub for United Nations Academic Impact and the International Association of Universities [73]
	UIO (University of Oslo)	SDG are frequently mentioned on website [74]
	NMBU (Norwegian University of Life Sciences)	SDGs are mentioned on website [75]
	University of Tromsø—The Arctic University of Norway	SDG research and education event [76]
	University of Stavanger	SDG education and research projects [77]
	University of Agder	SDG education and research [78]
	University of South-Eastern Norway	SDG education and research [79]
	OsloMet—Oslo Metropolitan University	SDG education and research [80]
	Nord University	SDG research [81]

We reviewed the Norwegian government's official follow-up report on the SDGs, which is publicly available on the ministry of foreign affairs website.

In a list published by slamonbuisness.com for the largest salmon producers in 2019, classified according to their production size in kilotons per year, 11 out of the top 20 companies were Norwegian. We reviewed these 11 companies and found that four of them do not have the practice of annual sustainability reports, and one company has no mention of the SDGs. The selected six companies are the largest producers in Norway and do have annually released sustainability reports. Furthermore, because we are focusing on the entire value chain, we included the salmon-feed producers in Norway with the reviewed companies. We looked for the largest salmon-feed producers. Based on experts' advice, we identified the four major feed corporations, one of which is also a salmon producer, and all four were selected for review. Norway currently has 10 universities, 8 university colleges and 5 scientific colleges owned by the state. We reviewed the Norwegian universities websites, excluding colleges and specialized education institutes by conducting a search on the universities webpages through the use of their online search engine. The following search words was used: Sustainable development goals, SDG, Agenda 2030.

Findings categorized and detailed under the TCSAS five steps will be presented in support of the TCSAS framework validation.

2.3. Framework Application

First step: Tag the Norwegian salmon value chain on the SDG stakeholders' commitment map.

There is a clear governmental commitment toward the SDGs since their announcement in 2015. "At a time when we need more, not less, global cooperation, the 2030 Agenda for Sustainable Development is the roadmap ensures everyone wins, even at the national level"—quote from Norwegian Prime Minister Erna Solberg at UN General Assembly 2019. There is a Norwegian governmental follow-up on the progress of the SDG transitional process [61]. At the industrial level **(private sector)**, the national association for seafood producers in Norway reported "aiming to contribute" to the progress of SDG achievement [82]. Annual sustainability reports from major companies in the NSVC mentioned the SDGs and presented the company's efforts toward their progress [69]. In 2016, corporate leaders and CEOs of the salmon industry in Norway and 12 other countries included the SDGs as part of the Global Salmon Initiative (GSI), with a clear voluntary commitment to the SDGs [83]. A National Committee for Agenda 2030 (SDG Norway) in higher education was formed in 2018 to strengthen the role of universities as relevant actors in the global endeavor raised by Agenda 2030 [73]. Evidence of commitment to the SDGs was found in the system's three most involved stakeholders: government, academia, and industry (see Figure 4).

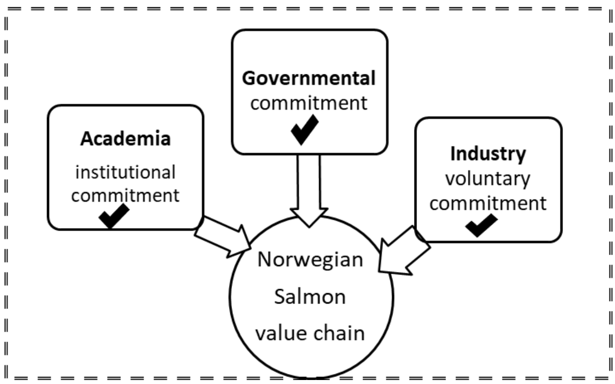

Figure 4. Stakeholders' commitment to SDGs.

Second step: Complexity analysis of the system's structure.

By reviewing the NSVC's structure [24,28,84–86], we identified certain structural, dynamic, and sociopolitical elements in the system that might add to or reduce its level of complexity in relation to SDG integration (see Table 5).

Table 5. NSVC system's complexity in relation to SDGs.

Complexity Category	Complexity Element	Adding	Reducing	Reason
Structural	Geographical expansion	0	1	• International perspective, raise interest in SDG.
	Multiple operational subsystems	1	0	• Require continuous/extended control and data acquisition.
	Environment (marine and land)	1	1	• Norway's environment is regulated and monitored. • Raw material from multiple countries.

Table 5. *Cont.*

Complexity Category	Complexity Element	Adding	Reducing	Reason
Dynamic	Research and development	0	1	• Persevere research, well-funded, institutional. • Several challenges still under research for solutions.
	Large corporations with centralized decision making	0	1	• Embracing change by top management can guarantee compliance by the entire value chain. • Gives more value for voluntary commitment to SDGs.
Socio-political	Societal support for sustainability	0	1	• Governmental commitment to SDGs. • Social interest in environmental wellbeing and sustainability.

Third step: System's communication channels.

The SDGs are present in stakeholders' communications and the associated literature. The NSVC information pool is nourished by input from institutions that are committed to the SDGs. This input is communicated through the channels of published research literature and education discourse [87] for professionals who serve the industry. The engagement of a broad range of researchers in scholarly discussions about SDG implementation is central [88]. Expanding the discussion to involve more groups of interest in the NSVC can be described as an area for further development. The system is regulated by governmental institutions that are committed to the SDGs; this is clearly communicated in the media, official websites, and reports. In addition, the Norwegian practices of science-industry platforms, conferences, and consortiums are a significant channel for communications about the SDGs. The practice of releasing annual corporate sustainability reports is common among Norwegian seafood corporations. Reports communicated to the public on company websites contribute to transparency and collective knowledge about the SDGs. Annual corporate sustainability reports can reflect the system's responsiveness to the SDGs, a feedback loop of information from companies to the SDG-committed society about the integration of SDGs in the operational structure of the NSVC.

Fourth step: Align the system's data with the global indicator framework.

The NSVC's available data is systemically gained through a well-established methodology. Reviewed reports, published information, and statistics display the system's data acquisition capabilities, which can be described as high. The system's existing data in relation to the SDGs can be categorized as social, environmental, and economic. Official statistics on the salmon industry are publicly available on the Norwegian statistics bureau website [31]. The NSVC has an environmental database that can cover many of the SDG requirements; the methodology of life-cycle assessment (LCA) has been a common practice in this industry to assess environmental impacts [89]. Scientific research and data acquisition on salmon production and sustainability is a continuous endeavor in Norwegian universities [28,89,90]. Besides the environmental data, there are data on material-efficient utilization, food, nutrients, the societal contribution of employment, gender equality, and revenue, all of which were presented in the reviewed corporate sustainability reports [54–63].

Fifth step: Sustainability key performance indicators (KPIs), obtained from SDGs.

A key performance indicator (KPI) is a measurable value that demonstrates how effectively a company is achieving objectives. Companies present their revenue, number of jobs, gender balance in employment, material utilization efficiency, environmental impact, and related practices as KPIs of the company's progress. The NSVC's major companies release annual sustainability reports that reflect the continuous search for more KPIs on all aspects of production and perspectives of sustainability. The reviewed corporate sustainability reports from the NSVC showed several SDG-driven KPIs. The reported KPIs reflected companies' efforts and achievements on protecting the ocean, community empowerment, responsible production, climate action, and partnerships for SDG achievement. Adopting the SDGs with a clear commitment, including using their indicators as KPIs and referring to them in annual corporate sustainability reports, is a common feature of the NSVC. However, there are different levels of SDG inclusion as KPIs between the different companies, ranging from total integration and usage of SDG terminology, icons, and associated indicators to limited mentions [64,69,91–93]. The reviewed corporate sustainability reports indicate that SDGs are a thriving trend in the NSVC's corporate reporting and communication culture (see Table 6).

Table 6. Examples of KPIs derived from SDGs found in the reviewed reports.

Company	Reference	Examples of: KPIs	SDG
Lerøy	report [63]	• 50% reduction in the use of non-recyclable plastic by 2024 • Participation in multi-stakeholder initiatives • Food waste reduction	Goal 14 Goal 17 Goal 12
MOWI	report [64]	• Energy use and GHG emissions • Percentage of sites with minimum benthic Impact. • Training on diversity and equal rights	Goal 12 Goal 14 Goal 8
Grieg	report [65]	• Minimum usage of hydrogen peroxide treatment • Carbon footprint reduction • Reduction in the use of plastic in production	Goal 14 Goal 13 Goal 12
Nova Sea	report [66]	• Zero antibiotics usage • Reducing Co2 emission per kg of salmon	Goal 14 Goal 13
SALMAR	report [67]	• Higher 12 month rolling survival rate • Omega-3 production	Goal 14 Goal 3
Cargill	report [68]	• Increase resource efficiency of farmed fish • 35% trimming of marine ingredients	Goal 14 Goal 12
BIOMAR	report [69]	• Fish feeds are 50% circular and restorative by 2030 • 20% reduction per kg of feed by 2020	Goal 14 Goal 2
Cermaq	website [70]	• Increasing share of plant-based feed • Cut GHG emissions by 35% by 2030	Goal 14 Goal 13
Skretting	report [71]	• Operational actions to reduce impact through KPIs • 50% reduction in antibiotic usage	Goal 13 Goal 14

3. Discussion

The six-step method is a structured approach based on a logical systematic order to systemic challenges. The developed TCSAS framework came about as a result of the SE approach of the six-step method application. By applying the TCSAS framework to the NSVC case, we can see that the system's host country's official government's commitment to sustainability—in general, and to the UN SDGs in particular—is driven to embrace the SDGs within the operational structure of the system. The heavy influence of the governmental stakeholder in shaping the vision for development and related policies [89] was deployed in favor of SDG integration. A lack of political will is not found to be a roadblock between aquaculture and SDG implementation in the NSVC, in contrast to previous findings [94]. The TCSAS framework relied on understanding the value chain's structure, operational dynamics, and sociopolitical reality as a prerequisite to identify its complexity and adaptability to the integration of SDGs. In this study, the NSVC is seen as a moderate-complexity system in its SDG relation, with more complexity-reducing than complexity-adding factors. The geographical expansion of the NSVC over several countries is a significant consideration, starting from where the basic raw material is produced and then imported to the aquaculture production sites in Norway all the way to the product export destinations all over the globe. This international presence gives more importance to the global perspective of sustainability and the SDGs. The NSVC is structured around salmon feed production from plant material and marine material, then progressing to salmon-farming in sea cages in the marine environment. Clearly, both environments—land and marine—are impacted by this industry and must be included in any sustainability endeavor. Findings of the academic stakeholder (universities) point out that the NSVC is supported by continuous research and development, making it a dynamic system that can embrace change with a high capacity for adaptation despite the presence of certain complexity-adding factors. Responsive communication between the system's stakeholders and system's operational structure is the main channel for the SDGs to flow into the system. The SDGs' appearance in stakeholders' communications, the literature, educational discourse, websites, reports, etc., is indirectly inviting a response from the industry on the issue of SDG implementation. The empirical findings showed evidence of voluntary commitment to SDGs in the industrial private sector. A milestone example is the global salmon initiative [83]. Academia is considered by this study as a major stakeholder in embracing the SDGs; the findings confirmed that Norwegian universities are engaged in the process of SDG integration. Most of the scientific research on the NSVC is taking place in universities, where most of NSVC's skilled workforce is being educated. The SDGs are frequently mentioned on universities' official websites and presented within education programs, sustainability projects, and in their published research work. "It is vital for Norway to have a national action plan for the Sustainable Development Goals and only natural for academia to inhabit a key role by contributing with research-based knowledge and critical thinking on the goals," says Vice-Rector Annelin Eriksen at the 2019 National SDG Conference, University of Bergen. The sustainability reporting from a global value chain must have the qualities of being internationally directed, considerate of product life cycle from source to sink, and holistically covering all sustainability criteria. Adopting SDG in NSVC's communications provides globally understood terms to describe NSVC's sustainability endeavors, this advantage motivates for further inclusion of the SDG. Moreover, the presence of SDGs in the sustainability communications of global value chains is becoming highly anticipated [95]. The occurrence of import/export operations and the expansion of the NSVC over several countries creates a need for international common ground and terminology for communicating sustainability performance. Defining the coordinates of where the local system is standing relative to the global agenda and highlighting the points of intersection will upgrade the communication and performance on sustainability within the corporate culture. The existing corporate practices, considerate of local environmental protection and societal and economical welfare, are also serving collective global sustainability. The communication on SDGs from companies to other stakeholders requires providing relevant performance data. The purpose of including the SDGs in corporate culture and practices is not only as a vision for the future but also as a systemic data-based framework for development. The corporate practice of releasing an annual sustainability report with supporting data to the claims of achievement to the public is seen by this study as a cornerstone in the SDG integration process. Communicating sustainability information from companies to system's stakeholders who are voluntarily committed to the SDGs, might lead to mentioning the company's commitment to SDGs in its mission statement or general policy. The question of what benefits might interest the companies in committing to SDGs is a start point to understand how UN SDGs can introduce new concepts that will improve the system's local reality in relation to sustainability.

Such a perspective might raise the awareness of responsibility toward global sustainability, both at the corporate and societal levels. The SDGs' general perspective for a sustainable value chain is that it is profitable throughout all its stages and provides broad benefits for society with a positive or neutral impact on the environment. SDG-guided value chains must adopt the full life-cycle perspective, expanding the focus from basic raw material obtainment to the endpoint of the product, including its processing, supply, delivery, and waste. Companies are key functional structures in the process of integrating the SDGs into value chains. Larger companies (corporations) have larger sustainability-related impacts that are spatially spread over different countries. Corporate activities severely affect the present and critically impact the future, and for that reason, corporate sustainability is necessary for the long-term sustainable development of the economy and society [96]. There is a general agreement that a value chain's success and survival require consideration for sustainability [97]. A value chain's economic, environmental, and social performance may significantly benefit from integrating SDGs into their standard business practices. Integrating SDGs into corporate strategy can be achieved by developing the most appropriate KPI system to create a strategic alignment with the global indicators framework [98]. Developing a KPI that serves the SDGs within the value chain is a collective task that requires efficient communication, partnerships, empowerment of the involved, and a high level of commitment [99]. The communication on SDGs is more prominent in companies with high business volume and regular release of sustainability reports on their official websites [100]. This correlation is clearly observed in the NSVC.

4. Conclusions

The suggested framework (TCSAS) managed to provide system insight on the integration process of SDGs within the NSVC. Communication on SDGs by NSCV stakeholders progresses into responsive, data-supported reporting from the operational structure on its status of commitment and performance in relation to the SDGs. Internationally operating value chains have an interest in embracing SDGs into their sustainability endeavors due to the SDGs' global nature. This study showed that after six years from the declared Norwegian governmental commitment to the SDGs, the SDGs were found to be present in the largest companies in the NSVC, as evidenced in their issued annual sustainability reports. This reflects the relative efficiency of the top-down approach. The academic institutions are creating a pool of knowledge about the SDGs' value, which is accessible by the industry. We see that the SDGs' optimum form of integration in an industrial system materializes as strategically adopted measurable key performance indicators (KPIs) associated with specific SDGs.

5. Limitations and Future Research

The level of SDG integration within the NSVC will progress further with time and gain more depth and breadth. There is the potential for a feedback loop of useful practical insights on the SDG integration process within the NSVC to the global stakeholders of the UN SDGs and other global value chains. It can carry new perspectives to serve SDG implementation in other value chains. This study investigated the system's available communication channels on SDGs without much focus on the "**Status of Dialectic**" within the system around the SDGs. Future research should be done on the adoption of each of the 17 SDGs and investigate their specific challenges. The framework proposed in this paper could be applied to other industries to gain insight into their SDG integration processes.

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