South African Kelp Farming Project (SA KFP):

Phase 2 Feasibility Study

Final Project Report

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Preamble

Kelp farming, a form of seaweed aquaculture, is a rapidly growing global industry with significant potential for both environmental and economic benefits. While East and Southeast Asian countries, particularly China, South Korea and Japan dominate current production, interest and investment in kelp farming are expanding to other regions, including America, Europe, and Africa.

South Africa (SA) boasts the major kelp forests in Africa, dominated by two main species namely *Ecklonia maxima* (sea bamboo) and *Laminaria pallida* (split-fan kelp). These kelp forests, found primarily along SA's west coast, form productive ecosystems that support a wide range of marine life. In addition, *Macrocystis pyrifera* (bladder kelp), which has been widely used in the seaweed industry in other parts of the world, occurs in a few small populations in southwestern SA. Kelp harvesting and collection for commercial purposes, particularly for plant growth stimulants and alginates, is a notable industry and, together with the abalone farming industry that requires kelp to feed abalone, have resulted in an increase in the demand for kelp in SA.

While the harvesting of fresh wild kelp and beach-cast kelp are currently the main focus, there is increasing interest in kelp aquaculture and the diversification of kelp-based products; however, in SA very limited information is available on the cultivation aspects and potential of the three local west coast kelp species *E. maxima*, *L. pallida* and *M. pyrifera*. As such, the South African Kelp Farming Project (SA KFP) was proactively commissioned to determine the potential for kelp farming in SA.

Phase 1 of the SA KFP (implemented over four months during 2021-2022) identified potentially suitable areas for kelp farming along the west coast of SA and based on preliminary market assessments, production and financial requirements, recommended the continuation to the Phase 2 Feasibility Study (implemented over three years from 2022 – 2025) that carried out the first successful full life cycle cultivation of the three local kelp species in an aquaculture setting in Africa.

This report outlines the achievements of **Phase 2 of the SA KFP** (conducted in Small Bay of Saldanha Bay) which include:

- ✓ successfully advocating for the amendment of the Environmental Authorisation to include farming of indigenous seaweed species in the Saldanha Bay Aquaculture Development Zone,
- ✓ tailoring publicly available hatchery and nursery culturing methods for all three local kelp species,
- ✓ trialling various grow-out production systems and obtaining yields on vertical droppers comparable to that obtained in countries such as the USA where kelps are farmed profitably,
- ✓ compiling Standard Operating Procedures (SOPs) for the kelp production cycle (hatchery, nursery, weaning, and grow-out methods),
- ✓ determining which biofouling species occur on the three kelp species that could possibly affect blade quality and ultimately the price when sold, and the seasonality of biofouling in local kelp aquaculture,
- ✓ determining the season most suitable for the three local kelps to be grown in Small Bay of Saldanha Bay by monitoring and comparing environmental factors, kelp growth and phytoplankton,
- ✓ analysing all three local kelps to assist with food safety standards and certification,
- ✓ conducting preliminary pre-processing trials to establish if two methods of blanching (i.e. boiling and/or steaming) could reduce the content of potentially harmful heavy metals, arsenic and iodine,
- ✓ developing a business planning guide for kelp farming in SA and an associated financial forecasting model with worksheets to assist with financial projections and planning,
- ✓ and producing a comprehensive kelp market assessment, value chain analysis and roadmap for the expansion and strengthening of the kelp value chain in SA to enable the development of a sustainable kelp farming industry in SA.

A conscious effort was made to communicate project information (as listed above) in a clear and accessible way, ensuring it would be easily understood by a diverse group of stakeholders, including the funder, community members, industry representatives, academics, government officials, and politicians. This included tailoring the language and presentation of the content to suit different levels of technical expertise and familiarity with the project.

Citation:

BSASA 2025. South African Kelp Farming Project (SA KFP) Phase 2 Feasibility Study Final Report – Oct 2025

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Glossary of Terms

General Acronyms

AASA	Aquaculture Association of Southern Africa
ADZ	Aquaculture Development Zone
AMC	Aquaculture Management Committee
ASTRAL	All Atlantic Ocean Sustainable, Profitable & Resilient Aquaculture
BOM	Blue Ocean Mussels
BSASA	Bivalve Shellfish Farmers Association of South Africa
DFFE	Department of Forestry, Fisheries and the Environment
DSTI	Department of Science, Technology and Innovation
EA	Environmental Authorisation
EC	European Commission
EMPr	Environmental Monitoring Programme
EU	European Union
FAO	Food and Agricultural Organisation
FCDO	Foreign, Commonwealth & Development Office
GSC	Global Seaweed Coalition
IMTA	Integrated Multi-Trophic Aquaculture
IUCN	International Union for Conservation of Nature
NOAA	National Oceanic and Atmospheric Administration
PA	Project Assistant
PM	Project Manager
POC	Paternoster Oyster Company
PSA	Project Scientific Advisor
PSSA	Phycological Society of Southern Africa
RAs	Research Assistants
SA	South Africa
SABS	South African Bureau of Standards
SA KFP	South African Kelp Farming Project
SARIH	Southern Africa Research and Innovation Hub
SOPs	Standard Operating Procedures
UCT	University of Cape Town
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNOC	United Nations Ocean Conference
USA	United States of America
UWC	University of the Western Cape

Scientific symbols and acronyms

AA	Arachidonic Acid
Al	Aluminium
As	Arsenic
CB	Chlorinated Biphenyl
Cd	Cadmium
cm	Centimetre
Co	Cobalt
Cr	Chromium
Cu	Copper
°C	Degrees Celsius
DHA	Docosahexaenoic Acid
DMA	Dimethylarsinic Acid
DO	Dissolved Oxygen

DW	Dry Weight
EPA	Eicosapentaenoic Acid
f/2	Guillard f/2 Enriched Seawater medium
FAs	Fatty Acids
Fe	Iron
g	Grams
GC/FID	Gas Chromatography with Flame-Ionization Detection
GeO_2	Germanium dioxide
Hg	Mercury
H_2SO_4	Sulfuric Acid
I	Iodine
IC-ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled plasma Optical Emission Spectroscopy
K	Potassium
kg	Kilograms
MeHg	Methylmercury
ug	Micrograms
µm	Micrometres
mg	Milligrams
min	Minute
ML	Maximum Level
MLR	Maximum Residue Limit
MMA	Monomethylarsonic Acid
Mn	Manganese
MUFA	Monounsaturated Fatty Acid
Na	Sodium
Ni	Nickel
P	Phosphorus
PAH	Polycyclic Aromatic Hydrocarbon
Pb	Lead
PCB	Polychlorinated biphenyl
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
PES	Provasoli Enriched Seawater medium
pg	Picograms
PUFA	Polyunsaturated Fatty Acid
PVC	Polyvinyl chloride
Sb	Antimony
Se	Selenium
SEM	Standard Error of Mean
SFA	Saturated Fatty Acid
SPE	Solid Phase Extraction
t	Tonne
V	Vanadium
WW	Wet Weight
Zn	Zinc

Executive Summary

Kelp farming, a form of seaweed aquaculture, is a rapidly growing global industry with significant potential for both environmental and economic benefits. While East and Southeast Asian countries, particularly China, South Korea and Japan dominate current production, interest and investment in kelp farming are expanding to other regions, including America, Europe, and Africa.

In South Africa (SA), the harvesting of fresh wild kelp and beach-cast kelp are currently the main focus and there is increasing interest in kelp aquaculture and the diversification of kelp-based products. However, limited information is available on the cultivation aspects and potential of the three South African west coast kelp species *Ecklonia maxima*, *Laminaria pallida* and *Macrocystis pyrifera*.

The Foreign, Commonwealth & Development Office (FCDO) delivers science, technology and innovation partnerships to maximise the United Kingdom's (UK) development impact internationally. It is within this context that the South African Kelp Farming Project (SA KFP) was proactively commissioned in recognition of the opportunity to potentially develop a sustainable kelp farming industry in SA that can contribute to job creation, support food security, improve marine ecosystems and align with broader blue economy initiatives.

The overall goal of the project was to gather, analyse and disseminate evidence and research results (as per the project webpage and the project's YouTube channel) to a broad stakeholder base, including the existing aquaculture industry and new potential entrants to harness the potential benefits of a sustainable kelp farming industry that can contribute to the overall growth of the blue economy in SA.

The Phase 1 Pre-feasibility study (implemented over four months during 2021 - 2022) demonstrated positive potential for kelp farming in SA and identified Saldanha Bay in the Western Cape Province as a suitable trial location for the Phase 2 Feasibility Study (implemented over three years from 2022 - 2025) that carried out the first successful full life cycle cultivation of the three local kelp species in an aquaculture setting in Africa.

As part of our efforts to laying the foundations toward building a sustainable kelp aquaculture industry in SA, the key outcomes of the different project components included:

Hatchery & nursery component

- Numerous hatchery trials were conducted on the three local kelp species namely *M. pyrifera*, *L. pallida* and *E. maxima* at two experimental hatcheries (one at the Department of Forestry, Fisheries and the Environment [DFFE] Marine Aquaculture Research Facility and another at an industry-based facility at Paternoster Oyster Company [POC]).
- Although seasonal variation in the production of fertile material exists, fertile material of all three local kelp species can be found throughout the year for cultivation in the hatchery/nursery.
- Spores were successfully seeded over three growth years onto specialised seaweed string wound around PVC spools. These were placed in controlled conditions, initially in small containers (to minimise the chances of contamination) and later in larger tanks (with nutrient media and water movement provided). The latter 'nursery stage' proved a critical addition to procedures.
- Although some producers in other parts of the world place very small kelps in the sea (1 - 2 mm), we achieved much greater success with growing them to a larger size (~1 cm in length) in the

hatchery/nursery prior to being out-planted in grow-out. We believe this is due to conditions in Small Bay of Saldanha Bay showing considerable levels of biofouling and sedimentation, with larger kelps more able to survive early growth conditions.
- Juvenile kelps of all three species reached at least 1 cm in length in seven weeks at the POC based hatchery. Growth took longer at the DFFE based hatchery but was also successful in producing material for successful grow-out.
- The trials showed that all three species grow well in 15 °C sea water enriched with half strength PES growth medium, using a spore concentration of 2000 spores/ml for *E. maxima* and *L. pallida*, and 5000 spores/ml for *M. pyrifera*.

Weaning & grow-out component
- The grow-out site was situated at Blue Ocean Mussels (BOM) in Small Bay of Saldanha Bay on the west coast of SA which forms part of the Southern Benguela Upwelling System.
- Due to the high levels of sedimentation and biofouling in Small Bay of Saldanha Bay, we found that the introduction of a 'weaning stage' (where the PVC spools containing 1 cm kelp juveniles were hung for 2 - 3 weeks until they reached approximately 2 cm in length) provided the kelps with the opportunity to acclimatise and better survive until being unwound onto grow-out rope structures.
- Various grow-out structures were trialled at two positions at the BOM grow-out site where 6 - 7 m vertical rope droppers, suspended from long-lines, proved most successful.
- In Small Bay, *M. pyrifera* grew the best with *L. pallida* lagging behind, while *E. maxima* struggled to outcompete the biofouling species on the grow-out structures at the BOM site.
- The environmental monitoring conducted during the study period has indicated that the period between April-September each year is the optimal time to grow kelps in Small Bay. This is when nutrient concentrations are higher due to winter mixing and water temperatures during late March and early April drop below 15 °C, which is necessary when receiving the sporophytes from the hatchery/nursery where the spools are kept at 15 °C.
- The most common biofouling species on the blades of the kelps included skeleton shrimps, colonial bryozoans, hydroids, tube dwelling amphipods, mussel spat as well as red and green macroalgae. Arguably, the most problematic species for kelp farming in Saldanha Bay are the kelp lice and mussel spat. The kelp lice feed on the kelps (especially those showing poor growth) as well as the epiphytes on the kelps, whilst the mussels are fierce competitors for space on the grow-out ropes.
- While we have succeeded in growing the three kelp species (albeit with varying success), it should be noted that due to limited scale and grow-out time, we have not yet been able to determine the potential profitability of farming with kelps, although the research outcomes and lessons learned will contribute to ensuring profitability.
- The challenge for profitability in Small Bay will be the additional cost to clean and separate mussels off the kelps and kelp farming structures, and in general to scale from an experimental small-scale manually focused operation (as was done in Phase 2 of this project) to a larger more automated commercially focused operation (as is done in other parts of the world). In this regard, the financial forecasting worksheets (see section below) could assist with financial projections necessary to make sound investments.

Standard Operating Procedures (SOPs):
- Standard Operating Procedures (SOPs) are in general crucial for organisations because they ensure consistency, improve efficiency, reduce errors, and enhance safety by providing clear, step-by-step

instructions for how to perform tasks. This leads to better quality control, increased productivity, and improved regulatory compliance.
- The SOPs which were compiled by the Project Manager (available on the SA KFP webpage) were developed to provide future kelp farmers with a basis from which to work to fast track their own start-up initiatives.

Kelp nutritional analyses, food safety testing and pre-processing component
- Seaweeds are a rich source of essential macronutrients, micronutrients and bioactive molecules, but can accumulate toxic compounds when they are present in the surrounding environment.
- An on-going process to develop food safety standards for seaweeds in SA has been initiated by the South African Bureau of Standards (SABS) and the DFFE.
- To provide comprehensive baseline information on the nutritional content and potential food safety risks of South African kelps that will inform the development of food safety standards and promote their use as animal feeds and human food, wild (*L. pallida* and *E. maxima*) and cultivated (*L. pallida* and *M. pyrifera*) kelps were collected during Sep/Oct of 2023 and 2024 from Saldanha Bay to analyse their nutritional and chemical composition.
- Additionally, the effects of two blanching methods (boiling and steaming) on the heavy metal (cadmium, lead and mercury), arsenic and iodine content of *E. maxima*, *M. pyrifera* and *L. pallida* were investigated.
- The high nutritional value of South African kelps supports their use as valuable sources of proteins, minerals, and bioactive compounds for human and animal consumption, but continuous monitoring of chemical contaminants and heavy metals will be essential to mitigate potential health risks and ensure compliance with international food safety standards. Further optimisation of pre-processing methods should also be conducted to effectively reduce the content of harmful elements to improve food safety.

Amendment of the Environmental Authorisation (EA) for the Saldanha Bay Aquaculture Development Zone (ADZ):
- This component of the project was proactively commissioned because although the cultivation of *Gracilaria gracilis* was authorized in the EA issued by the DFFE in 2018, the three species targeted by this project (i.e. *M. pyrifera, L. pallida* & *E. maxima*) were not. Thus, a change of scope to the EA was required.
- The Environmental Consultancy Ecosense, drafted a desktop risk and/or benefit assessment which was submitted to the Saldanha Bay Aquaculture Development Zone (ADZ) Aquaculture Management Committee (AMC) for comment and the Competent Authority at DFFE for review. The Competent Authority approved Part 1 amendment in May'24 to amend the authorisation from specific reference to *G. gracilis* to include all indigenous seaweed species to the existing Environmental Authorisation for the Saldanha Bay ADZ.

Business Planning Guide for Kelp Farming & Financial Forecasting Model:
- Nautilus Growth Partners assisted with this component of the project, which was done in collaboration with the American National Seaweed Hub (funded by the Connecticut Sea Grant).
- The 'Business Planning Guide for Kelp Farming: South Africa' deals with writing a business plan with considerations for marketing, operations, financing and legal requirements etc. It is meant to be used with the Financial Forecasting Model worksheets, while considering information available in the Kelp

Value Chain Analyses & Market Assessment Report. The Financial Forecasting Model worksheets will assist interested parties with financial projections and enable the profitability of new ventures.

Value Chain Analysis, Market Assessment & Roadmap to develop a kelp farming industry:

- This component of the project was compiled by Advance Africa Management Services. The report maps and establishes the current market value for kelp in SA and identifies key gaps and inefficiencies within the value chain that, together with the financial forecasting sheets, need to be considered to ensure profitability of new ventures.
- The Kelp Value Chain Roadmap describes practical components that could be implemented to unlock opportunities for various parties (such as coastal communities, small-scale fishers, entrepreneurs, small businesses, researchers, funders, development agencies, academic and government institutions) interested in kelp farming in SA. It is premised on the successful development of kelp farming technologies investigated within this project. If the technologies provide reliable and commercially useful proof-of-concept, then the five roadmap strategies can be implemented. These include a Developmental/Regulatory Strategy, Research & Development Strategy, Product-Market Strategy, Commercialisation Strategy and Community Participation Strategy.
- The data presented in this report, along with the identified value chain inefficiencies, market opportunities and roadmap, establish a baseline that should be understood before embarking on or investing in kelp farming.
- Failing to grasp these insights may put kelp farming investors at risk of pursuing a production-driven venture instead of one driven by market demand.

Outreach and networking:

Various in-person outreach and information sharing efforts were undertaken both locally and internationally to disseminate evidence and research results to as broad a stakeholder base as possible. Additionally, a project webpage and YouTube channel were put in place by the Project Manager to assist with awareness creation of the SA KFP progress and information sharing.

Capacity building and training:

Internally, the project collaborated with two local universities (University of Cape Town [UCT] and University of the Western Cape [UWC]) to build capacity within the project while the Project Manager provided practical hands-on training and together with the DFFE staff and Prof Emeritus Bolton provided scientific supervision and guidance. Externally, the project collaborated with the United Nations Development Programme (UNDP) by attending and presenting at three community training workshop sessions in Saldanha Bay, St. Helena Bay and Velddrif.

A conscious effort was made to communicate project information (as outlined above) in a clear and accessible way, ensuring it would be easily understood by a diverse group of stakeholders, including the funder, community members, industry representatives, academics, government officials, and politicians. This included tailoring the language and presentation of the content (in this report, on the project webpage and the project's YouTube channel) to suit different levels of technical expertise and familiarity with the project.

1. Introduction to the SA KFP

The Foreign, Commonwealth & Development Office (FCDO) delivers science, technology and innovation partnerships to maximise the United Kingdom's (UK) development impact internationally. It is within this context that the South African Kelp Farming Project (SA KFP) was commissioned in recognition of the opportunity to develop a sustainable kelp farming industry in South Africa (SA).

The Bivalve Shellfish Farmers Association of South Africa (BSASA) is the delivery partner of the SA KFP responsible for the implementation of the multi-stakeholder project, supported by the Department of Forestry, Fisheries and the Environment (DFFE).

Phase 1 of the project served as a pre-feasibility study, investigating the potential for commercial cultivation of African kelp along the SA's west coast (implemented over four months from 2021 - 2022), which has informed the Phase 2 feasibility study (implemented over three years from 2022 - 2025) that carried out the first successful full life cycle cultivation of the three local kelp species in an aquaculture setting in Africa.

The Phase 1 pre-feasibility study demonstrated positive potential for kelp farming in SA, specifically *Ecklonia maxima*, *Laminaria pallida* and *Macrocystis pyrifera* which occur on the west coast of SA. *E. maxima* is characterised by a big holdfast that extends into one thick smooth long hollow gas-filled stipe of up to 15 m in length, ending in a bulblike structure that further extends into a primary blade from which secondary smooth blades of up to 3 m emerge and frequently break the sea surface. *L. pallida* on the other hand, is shorter and rarely breaks the surface of the water. From its holdfast grows a thick warty stipe that extends into a single smooth broad fan-shaped blade. Both *E. maxima* and *L. pallida* are common on wave-exposed shores, while *M. pyrifera* grows in shallow calm sheltered areas. From its holdfast grows multiple thin long stipes with numerous corrugated blades, each with its own gas-filled bladder at its base. Although nine potentially suitable areas for kelp farming along the west coast of SA were identified, Saldanha Bay was identified as a suitable trial location for the Phase 2 Feasibility Study due to the existing oyster and mussel farming industry and infrastructure availability within the established Saldanha Bay Aquaculture Development Zone (ADZ).

The Phase 2 Feasibility Study aimed to build on the Phase 1 achievements by furthering investigations into the following activities:

- Refining the kelp hatchery/nursery technologies
- Trialling kelp weaning/grow-out technologies in Small Bay of Saldanha Bay
- Monitoring environmental factors to assess environmental benefits/risks
- Assessing kelp quality for nutrient composition, food safety and certification
- Exploring value chain and employment opportunities
- Developing a Financial Forecasting Model for kelp farming

The overall goal of the project was to gather, analyse and disseminate evidence and research results to a broad stakeholder base, including the existing aquaculture industry and new potential entrants to lay the foundations toward building a sustainable kelp aquaculture industry in SA and the region.

As part of the project's efforts to disseminate evidence and research results as widely as possible, a project promotional video was produced along with a 5-part series of short videos capturing the essence of the project objectives and activities and these are available on the project webpage and the project's YouTube channel.

2. Purpose of the Phase 2 Final Project Report

The purpose of this report is to provide an overview of the activities and deliverables of the project. Detailed reports of the deliverables are attached to the annexure (in the case of the Hatchery & Nursery Report, Weaning & Grow-out Report and the Nutritional value, Food Safety & Pre-processing Report) and available on the project webpage (in the case of the Quarterly reports, Standard Operating Procedures, Business Planning Guide for Kelp Farming in SA, Financial Forecasting Model worksheets, as well as the Kelp Value Chain Analysis and Market Assessment report).

3. Phase 2 landscape

Although the BSASA was the delivery partner responsible for the implementation of the SA KFP, the project was a multi-stakeholder project with participants and collaborations as outlined below.

3.1 Project staffing, participants and collaborations

Funding support to the SA KFP was provided by the UK government via the FCDO for Phase 1 & 2, with BSASA as the lead implementing partner, supported by the DFFE.

The DFFE facilitates inter-governmental aquaculture research, links with the Department of Science, Technology and Innovation (DSTI) and provided support in the form of scientific expertise from key staff members. Additionally, the DFFE Sea Point Aquaculture Research Facility provided office and hatchery facilities to the project as outlined in Figure 1.

As part of BSASA's implementing team; a Project Manager (PM) from Sound Interaxions, a Project Accountant from Boland Financial Services, a Project Scientific Advisor (PSA), a Project Assistant (PA) and two Research Assistants (RAs) were appointed with the PA based at Paternoster Oyster Company (POC) and the RAs based at the DFFE's Sea Point Aquaculture Research Facility and Blue Ocean Mussels (BOM) farm respectively – see Figure 1.

As in the case with the DFFE, POC provided office and hatchery facilities to the project whereas BOM provided support and access to water space in Small Bay of Saldanha Bay. Additionally, Imbaza Mussels and Blue Sapphire Pearls assisted the project by providing boat and crew support (as outlined in Figure 1).

The project further collaborated with various institutions in its aim to fulfil its contractual obligations, and these included:

(a) collaborating with the Phycological Society of Southern Africa (PSSA) to host the SA KFP webpage on its website.
(b) collaborating with the University of Cape Town (UCT) via Senior Research Scholar Prof Emeritus John Bolton where the RAs were registered for Masters degrees while being employed in the project as Research Assistants.
(c) collaborating with the University of the Western Cape (UWC) via Prof. Gavin Maneveldt where two students were registered for a Masters and Honours degree respectively.

(d) collaborating with the United Nations Development Programme's (UNDP) "Exploring Seaweed Cultivation and Value Chains for Enterprise Development" project, led by Biosolutiones Technicas. This included attending three community workshops in Saldanha Bay, St. Helena Bay and Velddrif.
(e) contracting external consultants (such as Ecosense, Advance Africa Management Services, and Nautilus Growth Partners) to conduct specific project components and these are elaborated upon in Section 4.

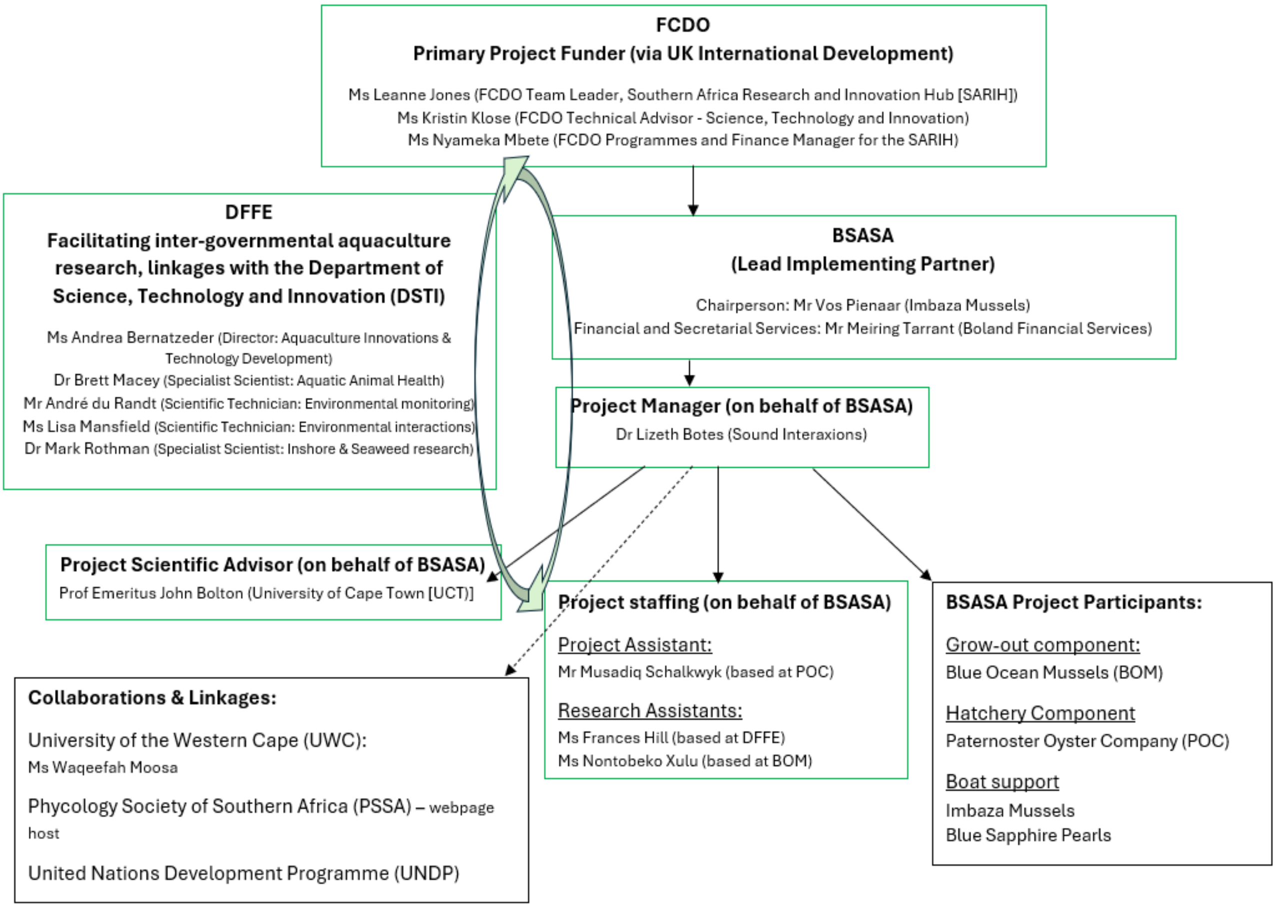


Figure 1: Diagram of project participants & collaborations

3.2 Project oversight and meetings

General monthly online Team Meetings were held between the BSASA Project Implementation Team, DFFE and the FDCO where strategic inputs were provided by Ms Kristin Klose, Ms Nyameka Mbete, Ms Andrea Bernatzeder, Mr Vos Pienaar and Dr Lizeth Botes (see Figure 1).
The entire project was managed by Dr Lizeth Botes and feedback on the budget spent was provided on a quarterly basis by Mr Meiring Tarrant and Dr Lizeth Botes.
Additionally, monthly in-person Research Meetings were held at the DFFE Sea Point Aquaculture Research Facility where research guidance and direction were provided by Dr Lizeth Botes, Dr Brett Macey, and Prof Emeritus John Bolton.
The two RAs namely Ms Frances Hill and Ms Nontobeko Xulu (both registered for Masters degrees at the UCT), were supervised by Prof Emeritus John Bolton, Dr Brett Macey, Dr Lizeth Botes and Dr Mark

Rothman, while Ms Waqeefah Moosa and Ms Zizipho Mfaku (registered for a Masters and Honours respectively at the UWC) were supervised by Dr Lizeth Botes and Prof Gavin Maneveldt (UWC).
Dr Brett Macey and Dr Lizeth Botes provided day-to-day supervision and guidance to Ms Frances Hill while Dr Lizeth Botes provided day-to-day supervision and guidance to Mr Musadiq Schalkwyk and Ms Nontobeko Xulu.

3.3 Reporting & information sharing

Reporting by the PM (Dr Lizeth Botes), was done in the form of quarterly reports and these are available on the project webpage, whereas the PA (Mr Musadiq Schalkwyk) and the two RAs (Ms Frances Hill and Ms Nontobeko Xulu) submitted weekly and monthly progress reports to their line managers while Ms Waqeefah Moosa submitted monthly reports between May'24 - Dec'25 to the PM.

Progress on project deliverables were communicated at the project's virtual workshop in Mar'23, the hybrid workshop in Mar'24 and the in-person project close-out event in Aug'25. Several other events were attended by various project members as outlined in Section 4.

Additionally, a project promotional video and a 5-part series of project videos were produced and these can be viewed on the project webpage and the project's YouTube channel.

4. Phase 2 outcomes & deliverables

To determine the feasibility of kelp farming on the west coast of SA, the project focused on the following components:

4.1 Hatchery & Nursery summary

Farming with kelps generally requires a hatchery component, where juvenile kelps are produced in a land-based facility before out-planting in the marine environment. There has been research recently on 'direct seeding', where the microscopic spores of the kelps are seeded directly onto substrates placed immediately in the sea, but evidence thus far suggests that this is much less efficient than traditional hatchery techniques.

A hatchery involves a space with a controlled environment where factors such as water temperature, light, nutrients and water flow, can be optimised to obtain the best growth and minimise the level of contamination by other marine organisms (see SOP 1). The aim is to produce spools, consisting of seeding string (also called hatchery twine) wound around polyvinyl chloride (PVC) piping, on which the microscopic stages of kelps are settled and the resulting kelp juveniles grown to a sufficient size in the required density to eventually produce an economically viable kelp crop after out-planting and eventual harvest. For the first week or so, growth takes place in small containers (such as jars) to minimise contamination, and later the spools are transferred to tanks with some added water movement (the 'nursery stage') to maximise nutrient uptake and growth.

Initially, in the method used during this project, the local kelps were collected as fertile material from specific portions of the kelp blades (see Annexure 7.2). The fertile tissue (also referred to as the sorus) produces billions of microscopic spores which undergo a detailed development process, via male and female microscopic gametophytes, to produce small kelp plants (also called sporophytes) within 2 - 3 weeks. Details of sorus collection, sporulation and early growth conditions, are available in SOP 2 - 7.

Although all three local kelps (*M. pyrifera*, *L. pallida* and *E. maxima*) produced fertile tissue that released spores all year round, it is possible that depending the species certain times of year are best for kelp development, although it should be kept in mind that the timing of seeding in Small Bay of Saldanha Bay will need to be synchronised with the timing/season of optimal conditions for kelp grow-out (see Section 5 & Annexure 7.3).

Despite considerable initial difficulties and through trial and error, the work carried out over Phase 2 of this project in the two hatcheries (DFFE and POC), has shown that both hatcheries proved capable of producing seeded spools of all three local species of west coast kelps (summary of results in Annexure 7.2). After several attempts, an initial phase with the spools maintained in jars (where the settled spores develop into gametophytes and eventually into small sporophytes) proved successful. This minimises contamination at this early stage. The introduction of a nursery phase (when the spools are transferred from the jars directly into larger tanks, with water motion to improve uptake of nutrients and dissolved gases) allow for the small sporophytes to grow up to 1 cm. The latter may provide more opportunity for contamination with other organisms, thus this stage must be closely managed as it is a careful balance between potential contamination and optimum growth conditions, which must be tested in each hatchery.

Numerous trials, as well as more controlled laboratory experiments in incubators, showed that all three local kelp species grow well in 15 °C, and it is not necessary to perform the expensive task of reducing the temperature to 12 °C for *M. pyrifera*, as is practiced elsewhere (e.g. Chile). Similarly, various levels of light, spore density, and two commonly used nutrient media were tested on sporophytes grown on microscope slides in crystallising glass dishes, however at this scale were not significant. Regardless, using a higher spore concentration was recommended (5000 spores/ml) to ensure optimum juvenile kelp development. However, the trials conducted at the POC based hatchery showed that a spore concentration of 2000 spores/ml for *E.maxima* and *L. pallida*, and 5000 spores/ml for *M. pyrifera* works well. The use of PES medium, originally designed for seaweeds, may be preferable to f/2 medium (the latter available in many aquaculture facilities and used to grow phytoplankton).

Throughout the project, development of kelps in the hatchery/nursery stages was quicker at the POC based hatchery facility (where sporophytes grew to ~1 cm in seven weeks) than at the DFFE based hatchery facility (where sporophytes grew to between 0.3 mm – 1 cm in twelve weeks). While it is difficult to be certain of the reasons for this, there are differences at the two facilities in system design, water supply, water treatment and the DFFE facility is also further from the kelp collection site than POC. Nevertheless, it became clear that there was a benefit in producing slightly larger sporophytes on seeded spools in the hatchery to outplant in Small Bay than are recommended in some other facilities overseas. To accommodate the high levels of biofouling and sedimentation at the grow-out site in Small Bay, we found that sporophytes should be around 1 cm in length before proceeding to weaning/grow-out, whereas some kelp hatcheries elsewhere out-plant sporophytes of only a few millimetres in length.

Additionally, the transport of PVC spools containing the juvenile sporophytes from the hatchery/nursery to the grow-out site is a critical stage in kelp aquaculture, particularly if the sites are distant (such as Sea Point to Saldanha Bay). Disturbance needs to be kept to a minimum and the temperature during transit should as far as possible be monitored and kept constant (~15 °C or below). At no stage should the kelps experience environmental shocks (see SOP 8).

4.2 Weaning & Grow-out summary

Saldanha Bay is situated on the west coast of SA, which forms part of the Southern Benguela Upwelling System. The grow-out site, located at BOM in Small Bay of Saldanha Bay, is approximately 12 m deep and was chosen due to its close proximity to the mouth of the bay, potentially providing access to the cool nutrient-rich waters of the Benguela Current during the upwelling season (September to March annually) when south-easterly winds are the primary driver of upwelling.

Various grow-out structures were trialled at two positions within the BOM grow-out site with 6 - 7 m vertical rope droppers proving to be by far the most successful (for more detailed results see Annexure 7.3). The introduction of a 'weaning stage' (as described in SOP 10) prior to unwinding the spools onto grow-out ropes, is crucial for successful out-plantings in Small Bay. Although all three target species were successfully out-planted, during 2024 *M. pyrifera* (26.6 kg total wet weight per 7 m dropper after eight months) by far outpaced *L. pallida* (12.3 kg total wet weight per 7 m dropper after six months) and *E. maxima* in terms of growth. In the case of *E. maxima*, the out-planting in Jan'24 was too early and did not survive past Mar'24 due to the biofouling outcompeting the *E. maxima*, and in Aug'24 it was out-planted too late and did not survive past Oct'24 when nutrient levels dropped to near zero and biofouling increased. During 2025, the observations of 2024 were confirmed with hardly any *E. maxima* left on the droppers by Sep'25 despite being out-planted at the recommended time (see Annexure 7.3 for more details). Yields of *M. pyrifera* and *L. pallida* were greatly impacted by severe biofouling during the 2025 grow-out season with the total wet weight of three *M. pyrifera* droppers being 23.11 kg/dropper, 17.69 kg/dopper and 17.91 kg/dropper respectively after six months, while the total wet weight for three *L. pallida* droppers being 10.05 kg/dropper, 3.12 kg/dropper and 3.46 kg/dropper respectively after six months. This demonstrates the year-to-year variation that is possible in kelp farming depending on the prevailing environmental factors such as monitored in this project. Nevertheless, based on the 2024 data, if 65 droppers (2m apart) were suspended from a 100 m longline, it would amount to yields just short of 2 tonnes in the case of *M. pyrifera* and just short of 1 tonne in the case of *L. pallida*. This is comparable to the yields obtained with *Saccharina latissima* (~10 kg/m thus 1 t/100m longline) which is being farmed profitably in the United States of America (USA).

The environmental monitoring conducted during the study period has indicated that the period between April - September each year is the recommended time to grow kelps in Small Bay when nutrient concentrations are higher due to winter mixing and when water temperatures during late March and early April drop below 15 °C to receive the sporophytes from the hatchery/nursery (see SOPs 9 - 12) where the spools are kept at 15 °C. As soon as the upwelling season starts in September continuing through to March each year, water temperatures range between 10 - 22 °C and nutrient levels drop to near zero (with the exception of the occasional upwelling event, especially at 6 m). During this time, the higher average phytoplankton cell concentrations contribute to the drop in nutrient levels which is important to both phytoplankton and kelps. This increased phytoplankton biomass (responsible for primary production) sustains the zooplankton (responsible for secondary production) which in turn sustains the entire marine food web in the months to follow, including the diversity of biofouling species (refer to Annexure 7.3 for more detailed results).

Biofouling refers to the settlement of organisms on natural and artificial surfaces and include epibionts which either attach to biological substrates like kelp blades for all or part of its life cycle. Kelps are known to support diverse communities of epiphytes (micro- and macroalgae growing on macroalgae) and epifauna (animals inhabiting the surface of other aquatic animals and/or macroalgae). The species richness of epiphytes and epifauna on *Macrocystis* (total of 38 biofouling species) was much greater than on *Laminaria* (total of 27 biofouling species) and *Ecklonia* (total of 30 biofouling species). One of the reasons for this may be attributed to the morphological difference between the blades of *Macrocystis* (being corrugated and easier to settle on) as opposed to that of *Laminaria* and *Ecklonia* (being smooth and more difficult to settle on). However, despite the higher species richness of biofouling species on the blades of *Macrocystis*, it appears that *Macrocystis* is more capable of outcompeting these species either because it was in general healthier and grew faster (in comparison to *Laminaria* and *Ecklonia*), as it is better suited for the prevailing conditions in Small Bay, has better self-defence and/or self-cleansing mechanisms or a combination thereof. Although both epiphytes and epifauna were present on the blades of all three kelps, the most common biofouling species on the blades of the kelps included skeleton shrimps, colonial bryozoans, hydroids, tube dwelling amphipods, mussel spat as well as other red and green macroalgae. The most common biofouling on the main long-line and farm structures included tunicates on weights, encrusting barnacles and mussels on buoys and anchor lines, skeleton shrimps and mussels on ropes and various macro-algae on ropes. Arguably, the most problematic species are the kelp lice and mussel spat. The kelp lice feed on the kelps (especially those which are showing poor growth) as well as the epiphytes on the kelps, whilst the mussels fiercely compete for space on the droppers of all three kelp species, but becomes especially problematic in the case of *Ecklonia* (and to an extent *Laminaria) ,* which seems to need rougher water to assist in keeping the blades healthy, minimise competition with biofouling species and ensure good growth.

Due to the change in the hydrodynamics of Saldanha Bay, which was altered by the construction of the man-made breakwater and iron ore jetty during the 1970s, leaving Small Bay much more protected than Big Bay and Outer Bay, it is unlikely that the kelp farming season as determined for Small Bay would be identical for Big Bay and Outer Bay. While Big Bay experiences rougher conditions (and possibly more favourable for *L. pallida* and *E. maxima* farming), it will undoubtedly still be challenged by excessive mussel fouling (as in the case of Small Bay). Outer Bay and other more open ocean sites may offer better access to nutrient-rich cold water from the Southern Benguela Upwelling System, potentially allowing for year-round kelp farming, but such sites will no doubt require farming systems engineered for the powerful ocean wave energy along the South African coast.

To fully understand how kelp farming can be done sustainably in SA, it will be best to do a similar study with the appropriate farming systems at sites with less or no mussel fouling pressure. Perhaps more importantly, even if kelp farming is possible, it is crucially important to establish if it can be done profitably and if indeed it will make business sense. The challenge for profitability will be to scale from a small-scale manually focused operation (as was done in Phase 2 of this project) to a larger more automated focused operation (as is done elsewhere in other parts of the world). While we have not yet had the opportunity to do a project at scale, this project has yielded several lessons that will lay the foundation and contribute to profitable kelp farming initiatives in SA.

4.3 Nutritional analyses, food safety tests and pre-processing summary

There is an ever-increasing demand for seaweeds (especially kelps) for use as food and food supplements and seaweed cultivation has also been shown to have positive ecosystem impacts. However, the extractive abilities of seaweeds mean they can accumulate other elements, including certain trace elements and heavy metals and other toxic compounds should they be present in the environment. Since the accumulation of these compounds is dependent on seaweed type, physiology, season, and environment, it is essential to examine the nutritional and chemical composition of seaweeds at or near the site of cultivation to determine potential benefits and/or risks should these seaweeds be considered as feed for animals or food for humans. Moreover, should risks exist, methods should be developed to mitigate these risks. Currently, there are no specific Codex or international standards addressing food safety in seaweeds, and regional or national legislation on hazards remains largely undefined. While some countries like the European Union (EU) e.g., France and Germany, and China have established threshold levels for certain heavy metals, metalloids and trace elements in seaweed products, these regulations are limited and vary between regions. In SA, efforts are underway by the South African Bureau of Standards (SABS) and the DFFE to develop comprehensive food safety standards for seaweeds, such as kelps, that are being considered as food for humans or feed for animals—but information on the nutritional and chemical composition of local kelps is lacking. Therefore, the objective of this study was to investigate the nutritional value and potential food safety risks, and approaches for reducing heavy metal, arsenic and iodine content, of wild and farmed South African kelps (*M. pyrifera*, *L. pallida*, and *E. maxima*) in Saldanha Bay in the Western Cape Province of SA.

Wild (*L. pallida* and *E. maxima*) and cultivated (*L. pallida* and *M. pyrifera*) kelps collected during Sep/Oct of 2023 and 2024 in the Saldanha Bay Aquaculture Development Zone (ADZ) (33°02'05"S 18°00'35"E) were transported to Forever Fresh (https://foreverfresh.co.za/) in Somerset West (near Cape Town) for freeze-drying and packing prior to being submitted to the laboratories of Mérieux NutriSciences for nutritional and/or food safety analysis (https://www.merieuxnutrisciences.com/za/). Wild kelps were tested for potential food safety risks—including dioxin-like and non-dioxin-like PCBs, dioxins and furans; perfluoroalkyl substances, polycyclic aromatic hydrocarbons (PAHs), metals (cadmium, lead, mercury, mercury speciation, arsenic, inorganic arsenic), and pesticides. Cultivated kelps were subjected to both food safety and nutritional analysis as well as pre-processing tests—allowing for a comparison of food safety risks and the nutritional content of wild harvested and cultivated kelps, and determination of the effects of pre-processing (blanching and/or steaming) for lowering the heavy metal, arsenic and iodine content of the three Southern African kelps.

Results from this analysis demonstrate that both wild harvested and cultivated kelps from Saldanha Bay have a high nutritional content (for more detailed results of all analyses see Annexure 7.4). The crude protein contents of cultivated *M. pyrifera* and *L. pallida* ranged from 11.13 – 13.81 %, suggesting that they're a good source of dietary protein for inclusion in animal and human food. The ash (macro-mineral and trace element) content of both seaweeds was also high (26.42 – 49.69 %), suggesting South African kelps could have important health benefits. Among the minerals, the content of iron (Fe), zinc (Zn), aluminium (Al), arsenic (As), sodium (Na) and potassium (K) was consistently the highest. Lipid contents were low, which is typical of seaweeds—with a lipid content of 0.78±0.09 and 0.82±0.096 % recorded for the *Macrocystis* and *Laminaria*, respectively. Polyunsaturated fatty acids (PUFAs) were the most abundant of the fatty acids (FAs) followed by the saturated fatty acids (SFAs) and monounsaturated fatty acids (MUFAs). The most abundant SFA was 16:0 (Palmitic acid), which accounted for 20.6±4.7 % and 17.1±3.9 % of the total FA methyl esters for *Macrocystis* and *Laminaria*, respectively. Of the MUFAs, 18:1n-9c (oleic acid) was most abundant in the kelps. Both kelps displayed a high content of the PUFAs 20:4n-6 (arachidonic acid; ca. 16 %) and 20:5n-3 (eicosapentaenoic acid (EPA); ca. 12 % in *Macrocystis*), while the content of DHA (22:6n-3) was much lower (<3 %) in both cultivated kelps. EPA plays an important role in human health (e.g., anti-inflammatory, anti-thrombotic and anti-arrhythmic) and may therefore provide numerous health benefits following consumption. The carbohydrate content of the cultivated kelps was high (60.09 and 40.57 $g.100g^{-1}$ DW for *M. pyrifera* and *L. pallida*, respectively), confirming findings for other seaweeds. Seaweed carbohydrates have known health benefits, reportedly contributing to weight loss, reduced cholesterol levels, and supporting a healthy gut microbiome.

Although seaweeds typically have a high content of beneficial minerals, they can also accumulate non-desirable (toxic) heavy metals and trace elements from their immediate environment. For both the wild harvested and farmed kelps collected from Saldanha Bay, the content of arsenic (As) > cadmium (Cd) > lead (Pb) > mercury (Hg). Seaweeds are particularly abundant in As due to their propensity to absorb marine arsenic, and kelps can concentrate As to relatively high levels even at natural concentrations. Levels of total (non-toxic organic and toxic inorganic) As recorded in all Saldanha Bay kelps were above the maximum levels (MLs) allowed for seaweeds used as feed(s) however, the levels of inorganic As were substantially lower (< 0.2 $mg.kg^{-1}$ DW) and well below the ML set by European Commission (EC) for seaweed used as feeds (2 $mg.kg^{-1}$) and French recommendations for edible seaweeds (3 $mg.kg^{-1}$ DW). The heavy metal with the second highest content was Cd, with the highest values recorded for cultivated *Macrocystis* (1.36±0.28 $mg.kg^{-1}$ DW), followed by wild harvested *Ecklonia* (0.73 – 0.95 $mg.kg^{-1}$ DW) and wild *Laminaria* (0.59±0.12 $mg.kg^{-1}$). These values all exceeded the maximum level of 0.5 $mg.kg^{-1}$ DW recommended by France for seaweeds that are used as feed and edible seaweed, and it is recommended that Cd be regarded as a contaminant that requires increased vigilance from a food safety/regulatory perspective. The levels of Pb in all Saldanha Bay kelps (highest value of 0.88±0.20 $mg.kg^{-1}$ DW recorded for cultivated *Macrocystis*) are well below the ML for feed (10 $mg.kg^{-1}$) and edible seaweed (5 $mg.kg^{-1}$) recommended by the EC and France. Mercury (Hg) content of most seaweeds are typically low and Hg was the heavy metal with the lowest concentration of all the non-essential metals in both the wild harvested and cultivated kelps collected from Saldanha Bay, with the recorded values (0.005 – 0.016 $mg.kg^{-1}$ DW) well below the ML for feed (0.1 $mg.kg^{-1}$) and edible seaweed (0.1 $mg.kg^{-1}$). Iodine (I) is an essential trace mineral for both humans and animals and is found naturally in seaweeds. In France, the recommended ML of iodine is set at 2000 $mg.kg^{-1}$ DW for all species of edible seaweed. The iodide content of the *M. pyrifera* and *L. pallida* analysed from Saldanha Bay was 1240±230 and 5340 $mg.kg^{-1}$ DW, respectively—similar to what has been reported for other brown seaweeds (1612–6568 $mg.kg^{-1}$ DW).

Due to limited information globally on the monitoring of pesticide residues in seaweeds, the EU has set a default maximum residue limit (MRL) of 0.01 $mg.kg^{-1}$ for most pesticides. Of the ca. 950 pesticides tested for in the current study, only two were detected in the South African kelps, Tribromoanisole and Tribromophenol. Tribromophenol occurred in all seaweeds (wild and cultivated) analysed from Saldanha Bay, whereas Tribromoanisole only occurred in the wild harvested *Ecklonia*. None of the other pesticides tested for were detected in this study. Several dioxin and dioxin-like PCBs were detected. Of the 19 PCBs monitored for in the kelps, 16 were detected in the cultivated *Macrocystis* and ranged in concentration from 0.007–8.4 $pg.g^{-1}$ DW, whereas 14 were detected in the cultivated *Laminaria* and ranged in concentration from 0.007–6.6 $pg.g^{-1}$ DW. However, more than 99% of the PCBs were below the cancer slope factor (CSF) limit from the USEPA Integrated Risk Information System database [8 $ug.kg^{-1}$ DW].

Seaweeds can accumulate a variety of harmful trace elements and heavy metals from their immediate environment, but among elements of concern, inorganic arsenic, cadmium, and iodine have been identified as major food safety hazards, while lead and mercury are regarded as moderate hazards. In the present study, the effects of two blanching methods—2-minutes of boiling or 20-minutes of steaming followed immediately by 5-minutes of rapid cooling in ice water—on the heavy metal (Cd, Pb and Hg), As and I content of *E. maxima*, *M. pyrifera* and *L. pallida* were investigated. We demonstrated that both boiling and steaming can significantly reduce the iodine content of all kelps, with the extent of the reduction being species dependent. Boiling was more effective for reducing iodine content, resulting in a reduction of 83.87 % ($p=0.004$), 58.92 % ($p<0.001$) and 70.37 % ($p<0.001$) for *Ecklonia*, *Laminaria* and *Macrocystis*, respectively. The effects of both pre-processing treatments were however not as pronounced for the other elements/metals, with no significant reduction observed in the content of As, Hg, Cd and Pb for either boiling or steaming for any of the kelps.

The high nutritional value observed in cultivated species like *L. pallida* and *M. pyrifera* supports their use as valuable sources of proteins, minerals, and bioactive compounds for human and animal consumption. Implementing pre-processing methods, such as boiling or steaming, can effectively reduce the content of certain elements like iodine, improving food safety; however, the variable effects on heavy metals suggest that further optimization is needed. Continuous monitoring of chemical contaminants and heavy metals in farmed and wild seaweeds will be essential for the development of food safety standards in SA to mitigate potential health risks and ensure compliance with international safety standards. In this regard, there are on-going efforts by the DFFE and other research organizations (including the Cape University of Technology, University of Cape Town and the French IRD) to monitor the nutritional content and/or food safety risks of seaweeds of commercial importance in SA and a committee has recently been established by the SABS and the DFFE to develop a draft seaweed standard. Overall, strategic research and development will optimize cultivation practices, processing techniques, and safety protocols, thereby enhancing the role of seaweed aquaculture in promoting health, environmental sustainability, and economic growth in SA and globally.

4.4 Starting a kelp aquaculture venture

The main objective of the SA KFP project was to lay the foundations for the development of a sustainable kelp farming industry in SA. Apart from the work that was done by the project team, additional consultants were contracted to assist with the following components:

- **Amendment of the Environmental Authorisation (EA) for the Saldanha Bay Aquaculture Development Zone (ADZ):**
  Environmental authorisation (EA) is a legal permit from a competent authority, that is required for activities which may have environmental impacts. This component of the project was proactively commissioned because although the cultivation of *Gracilaria gracilis* was authorised in the EA issued by the DFFE in 2018, the three species targeted by this project (i.e. *M. pyrifera, L. pallida* & *E. maxima*) were not. Thus, a change of scope to the EA was required.

  The Environmental Consultancy Ecosense was commissioned to do a desktop risk and/or benefit assessment to:
  - determine whether there is sufficient information available on the cultivation of the three targeted species to apply for a Change of Scope without further specialist studies,
  - document changes required to the existing Saldanha Bay Aquaculture Development Zone (ADZ) Environmental Management Programme (EMPr) to accommodate cultivation of the three targeted species in the future, and
  - to assess whether the Change of Scope would require a Part 1 or 2 application.

  The document was submitted to the Saldanha Bay ADZs Aquaculture Management Committee (AMC) and the DFFE Competent Authority for inputs and review. Subsequently, a Part 1 amendment was done to the EA was subsequently amended to approve the farming of "Indigenous seaweed species" in Saldanha Bay ADZ (see Annexure 7.1: DFFE letter).

Operators within Saldanha Bay can therefore apply for either a research permit (for trial purposes without sale) or for an amendment of their Marine Right in consultation with the AMC in order to proceed with installation of infrastructure and activities as they relate to seaweed farming. Although several other sites were identified in the Phase 1 Pre-feasibility study, uncertainty still remains around the suitability of these sites for growing the three kelps trialled in this study, therefore interested parties will need to apply for scientific research permits to trial seaweed cultivation outside of the Saldanha Bay ADZ.

- **Value Chain Analysis, Market Assessment & Roadmap to develop a kelp farming industry in SA:** This component of the project was compiled by Advance Africa Management Services. Kelp harvesting and collection for commercial purposes, particularly for plant growth stimulants and alginates, is a notable industry in SA and, together with the abalone farming industry that requires kelp to feed abalone, have resulted in an increase in the demand for kelp. The report maps and establishes the current market value for kelp in SA and identifies several value chain gaps and inefficiencies within the value chain. These include the lack of a local (Western Cape) food-grade processing facility, the paucity of supply to the niche restaurant market, an industry-wide supply inconsistency and difficulty with accessing raw product, a constrained and inefficient concession license system, as well as the lack of a kelp farming industry, which may constrain the supply of kelp to niche markets.

  The Kelp Value Chain Roadmap describes practical components that could be implemented to unlock opportunities for various parties (such as coastal communities, small-scale fishers, entrepreneurs, small businesses, researchers, funders, development agencies, academic and government institutions) interested in kelp farming in SA. It is premised on the successful development of kelp farming technologies investigated within this project, and together with the financial forecasting worksheets, need to be considered to ensure profitability of new ventures. If the technologies provide reliable and commercially useful proof-of-concept, then the five roadmap strategies can be implemented. These include a Developmental/Regulatory Strategy, Research & Development Strategy, Product-Market Strategy, Commercialisation Strategy and Community Participation Strategy.

  The data presented in this report, along with the identified value chain inefficiencies, market opportunities and roadmap, establishes a baseline that should be understood before embarking on or investing in kelp farming. Failing to grasp these insights may put kelp farming investors at risk of pursuing a production-driven venture instead of one driven by market demand.

- **Business Planning Guide for Kelp Farming & Financial Forecasting Model:**
  Nautilus Growth Partners assisted with this component of the project, which was done in collaboration with the American National Seaweed Hub (funded by the NOAA Sea Grant).

  The 'Business Planning Guide for Kelp Farming: South Africa' deals with writing a business plan with considerations for marketing, operations, financing and legal requirements. It is meant to be used with the Financial Forecasting Model worksheets, while considering information available in the Kelp

Value Chain Analyses & Market Assessment Report. The Financial Forecasting Model worksheets will assist with financial projections meant to feed into financial plans. Together these tools will significantly assist in de-risking new kelp farming ventures for researchers, investors and those interested in kelp farming.

- **Standard Operating Procedures (SOPs):**
  Standard Operating Procedures (SOPs) are in general crucial for organisations because they ensure consistency, improve efficiency, reduce errors, and enhance safety by providing clear, step-by-step instructions for how to perform tasks. This leads to better quality control, increased productivity, and improved regulatory compliance.

  Since Phase 2 of the SA KFP carried out the first successful full life cycle cultivation of *M. pyrifera*, *E. maxima* and *L. pallida* in SA, the SOPs which were compiled by the PM and available on the SA KFP webpage, were developed to provide future kelp farmers with a basis from which to work to fast track their own initiatives.

All the above-mentioned documents can be accessed on the SA KFP webpage.

4.5 Outreach & networking

As part of our ongoing efforts referred to in Section 3.3 to disseminate evidence and research results to a broad stakeholder base, including the existing aquaculture industry and new potential entrants, our outreach and networking efforts included:

Phycological Society of Southern Africa (PSSA) Conference:
In Jan'23, the PSSA Conference was attended where the SA KFP Phase 1 outcomes were presented during the special session on 'Kelp use in Southern Africa' (a workshop-themed session chaired by Prof Emeritus JJ Bolton) and subsequently published as a special issue in the journal Botanica Marina. As the Project Scientific Advisor (PSA), Prof Emeritus JJ Bolton also facilitated a networking lunch between the SA KFP and the Kelp Blue project from our neighbouring country Namibia. The two projects differ significantly in their aims and approaches (species and genetic material selection, length of cultivation time, 'inshore' versus 'offshore', cultivation depth, growth from cultured microscopic stages versus natural spore seeding etc.) and the members of the two teams spent time together at the conference discussing methods.

Kelp Blue visit:
The visit to Kelp Blue (Namibia) from 15-19 Jan'24 was kindly hosted by Mr M Fleischman (previously a Masters student of Prof Emeritus JJ Bolton at UCT and an employee of Kelp Blue at the time of the visit). During the interactions with the Kelp Blue team, the PM (Dr L Botes) highlighted the differences between the SA KFP efforts with Kelp Blue—a private company entering its commercial stage and focusing on the farming of the Californian strain of *M. pyrifera* only, while the SA KFP is a collaborative effort aimed at establishing a sustainable kelp farming industry in SA, investigating the potential of farming with the three indigenous kelp species on the west coast of SA.

The UNDP Project "Exploring Seaweed Cultivation and Value Chains for Enterprise Development":
As part of this project, the United Nations Development Programme (UNDP) hosted three community workshops on 12 Aug'24 (Saldanha Bay), 14 Aug'24 (Velddrif) and 16 Aug'24 (St Helena Bay). This

collaboration with the UNDP allowed the SA KFP the opportunity to share the project's progress to date at all three of the community workshops and to create awareness of the fact that results and outcomes from the SA KFP will be available on the project webpage to all interested parties. For information on the outcomes of these workshops, please access the UNDP report on the SA KFP webpage.

The International Blue Carbon Scientific Working Group-16th Annual Meeting:
The International Blue Carbon Scientific Working Group's 16th Annual Meeting took place from 2 - 5 Sep'24 in Cape Town, which was organised by Conservation International, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Union for Conservation of Nature (IUCN). The aim of the kelp session was to consider different aspects with regard to kelp farming and/or kelp restoration as Blue Carbon Initiatives and methodologies/challenges for Blue Carbon research. Here the PM presented not only on the project's progress but also pointed out factors that would need careful consideration for kelp restoration or kelp farming when considering Blue Carbon research.

Aquaculture Association of Southern Africa (AASA) Conference:
During the 2nd week of Sep'24, the Aquaculture Association of Southern Africa (AASA) Conference [co-hosted by EU Horizon 2020 All Atlantic Ocean Sustainable, Profitable & Resilient Aquaculture (ASTRAL) project] took place in Stellenbosch. The conference had a major seaweed component, which was coordinated and chaired by Prof. Emeritus JJ Bolton, where five project members (the PM, the PA, the two RAs and Ms W Moosa) presented on their respective components on behalf of the SA KFP. This was followed by a visit to the project grow-out site by the international delegation from the EU Horizon 2020 integrated aquaculture project ASTRAL.

Earthshot week & the Seaweed Road to the United Nations Ocean Conference (UNOC) 2025 workshop:
The 2024 Earthshot prize awards (founded by Prince William) took place during the 1st week of Nov'24 in Cape Town. During this week the Seaweed Road to UNOC 2025 Workshop (hosted by the Global Seaweed Coalition [GSC]) was held to convene policymakers, funders, corporates, NGOs, scientists, and UN member states to discuss the potential of seaweed to repair and regenerate our planet. The workshop is part of the GSC's efforts to highlight and promote the potential of sustainable seaweed cultivation as a climate solution. It further explored with stakeholders the challenges and opportunities in the African context where Ms A Bernatzeder and the PSA gave presentations, and they as well as the PM participated in breakaway sessions where the challenges were further un-packed. The PSA is a member of the Scientific Council of the GSC since its inception, and after the workshop was invited to be a member of the Expert Advisory Panel of the Earthshot Prize for 2025.

World Bank Group (ProBlue) Global Seaweed Summit:
The World Bank Global Seaweed Summit took place in South Korea from 28 - 29 May'25 where Ms A Bernatzeder gave a presentation on the status of seaweed aquaculture in SA. Information from the value-chain analysis as well as a brief overview of the SA KFP were included in the broader presentation to a wide range of industry and policy stakeholders.

Seagriculture EU Conference:
The Seagriculture EU Conference (17 - 19 Jun'25) attracted top speakers from all over the world in the seaweed industry to discuss the 'Roadmap for the European seaweed industry', seaweed investment

requirements, seaweed applications, business aspects and scaling-up as well us using seaweed as a tool for ecosystem services. The PM presented the SA KFP during the Seaweed Elevator Pitches and raised awareness of our efforts as the first ever presentation from SA at SeagricultureEU. The networking opportunities provided the PM with an opportunity to meet with an UK industry member (Atlantic Mariculture) who agreed to attend the SA KFP close-out event to further discussions on the potential development of a kelp farming industry in SA. The Conference Dinner at the Blue City (which hosts 55 start-ups and entrepreneurs in the circular economy) provided for additional networking opportunities where many discussions around the challenges in the seaweed industry took place.

Additionally, the kelp promotional video was screened at various events and expositions, including at the FCDO exhibition stand at the Science Forum South Africa in Dec'23 and again at the FDCO and DFFE exhibition stands in 2024.

4.6 Capacity building & training

The capacity building and training efforts during Phase 2 of the project, resulted in one Honours degree (Ms Z Mfaku) and three ongoing Masters degrees (Ms F Hill, Ms N Xulu and Ms W Moosa), as well as the training of the PA (Mr M Schalkwyk). These efforts were captured in the Capacity Building and Training short video, which can be accessed on the project webpage and YouTube Channel.

Student	Title	Status	Institution
Zizipho Mfaku (Honours)	An investigation of the phytoplankton species that may be associated with farmed kelp in Saldanha Bay, South Africa.	Completed	UWC
Waqeefah Moosa (Masters)	An investigation into epibiotic species that may be associated with farmed kelp in Saldanha Bay, South Africa	On-going, to be submitted end of 2025	UWC
Nontobeko Xulu (Masters)	Investigating grow-out aquaculture techniques for three kelp species, *E. maxima*, *L. pallida* and *M. pyrifera* under different environmental conditions in Small Bay of Saldanha Bay, South Africa	On-going, to be submitted in 2026	UCT
Frances Hill (Masters)	Investigating the hatchery methodology of three potentially commercially viable South African kelp species *E. maxima*, *L. pallida* and *M. pyrifera*	On-going, to be submitted in 2026	UCT

5. Lessons learned

Throughout the project, the lessons learned in terms of the kelp production cycle were captured in the PM's quarterly reports available on the project webpage and these are summarised as follow:

- **<u>Production cycle:</u>**
  Generally, in **land-based aquaculture farm facilities**, the production cycle is well known to include the following production stages i.e. Hatchery (where parent stock are maintained indoors to produce offspring), Nursery (where offspring are reared indoors until big enough to be introduced to a semi-outdoors area), Weaning (where offspring are being transitioned to better equip them to being grown outdoors), and Grow-out (where offspring are maintained outdoors until market size is reached).

In the SA KFP, we initially took the approach to move kelp sporophytes which are barely visible by eye, from the hatchery directly to grow-out and exposing them to the outside environmental elements without intermediary stages. While this approach may well work elsewhere, we have found that having all the stages as explained above is more successful in Small Bay. The inclusion of the intermediate stages i.e., nursery (where sporophytes were grown to ~1 cm even though we eventually end up having to accept some degree of micro-algal contamination) and weaning (where spools were hung in the sea for ~2 - 3 weeks before being unwound) have allowed the kelps from the nursery to have a better chance to compete with initial sedimentation and biofouling when out-planted in Small Bay. The weaning stage has repeatedly proven to be successful, providing the kelp sporophytes approximately 2 - 3 weeks to acclimatise, especially if the travel distance between the hatchery site and the grow-out site is far. However, the other school of thought to outplant the hatchery spools as soon as possible before hatchery contamination sets in and when the sporophytes are less than 1 cm in average length, is equally valid. Thus, each potential kelp hatchery facility and/or potential kelp farmer will have to assess the two options and see which will work the best depending on the distance between the hatchery and grow-out as well the conditions at the grow-out site.

Hatchery/Nursery component (~2 months)

Although Figure 2 provides a general timeline that will be useful to a future kelp farmer in terms of planning, one should be mindful that differences between hatchery set-ups may exist. For example, at the POC based hatchery facility all three kelp species grew to ~1 cm within seven weeks, whereas at the DFFE based hatchery facility *Ecklonia* and *Laminaria* grew to 0.5 cm in twelve weeks and *Macrocystis* grew to almost 1 cm in twelve weeks.

Transporting from the Hatchery/Nursery facility to the Weaning/Grow-out facility

When transporting the kelp sporophytes to the grow-out site, temperatures during transit must be kept stable and preferably between 12 - 15 °C. Therefore, when planning to transport kelp sporophytes from the hatchery to the grow-out site (and depending on the distance to be travelled) it is important to choose a cool overcast day, especially if an air-conditioned vehicle is unavailable. Care should be taken to maintain the temperature in the transporting canisters and cooler containers, and to note the sea water temperatures where the kelps will be out-planted to as far as possible prevent the kelps from getting a temperature shock, either from heating up in the vehicle and then out-planted in cold water or from putting them into canisters and coolers where it is cold and then being out-planted in water that is much warmer.

Out-planting

When considering a day to out-plant, choose a day that is cool with little to no wind (www.windguru.cz) for ease of working on the boat. If the boat has a cabin, put the coolers with canisters containing the spools with sporophytes in the cabin until arrival at the out-planting rope structures. It would be advantageous to look at the days prior to the out-plant day and consider which winds are blowing and what the prevailing sea surface temperatures are (and even to obtain a vague idea of which winds may have resulted in a nutrient influx). If possible, overcast days during early April with water temperatures below 15 °C would be ideal. When the coolers with canisters (containing the hatchery spools) arrive, it is worth recording the air temperature inside the cooler, as well as the water temperature inside the canister for record keeping purposes. If possible, all should be between 12 - 15 °C and closely match the sea surface temperature where the unwinding of spools onto the grow-out rope structures will take place to avoid giving the sporophytes a temperature shock.

Weaning/Grow-out component (~6 months)

We have repeatedly had success with the method of hanging spools at the BOM site at a preferred depth (i.e. 3 m) for 2 - 3 weeks (depending on the size of the sporophytes when out-planted) without unwinding the spools, serving as a 'weaning stage'. As soon as the sporophytes reached 2 - 3 cm, the spools were removed and unwound on the desired out-planting rope structures, serving as the grow-out stage. It should be noted though that it is recommended to unwind the spools before the sporophytes reach 3 cm and not to wait until they are 4 cm or bigger, as at that point the holdfasts of the sporophytes extend over the hatchery twine and when being unwound, there is a risk of damaging the holdfasts. Once in grow-out, kelps should be monitored monthly (see Figure 3). However, when getting closer to harvesting time it would be especially important to monitor the kelps more regularly in order to get the best quality blades with as little biofouling as possible, depending on the intended use of the kelp material.

- **<u>General time-line:</u>**

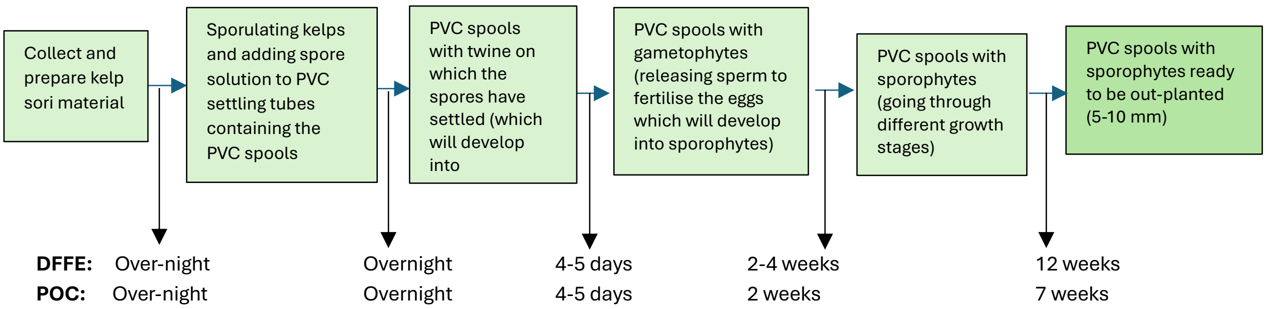


Figure 2. Timeline of all three species from collection of fertile kelp material to sporophytes ready for out-planting. (Diagram credit: Dr Lizeth Botes)

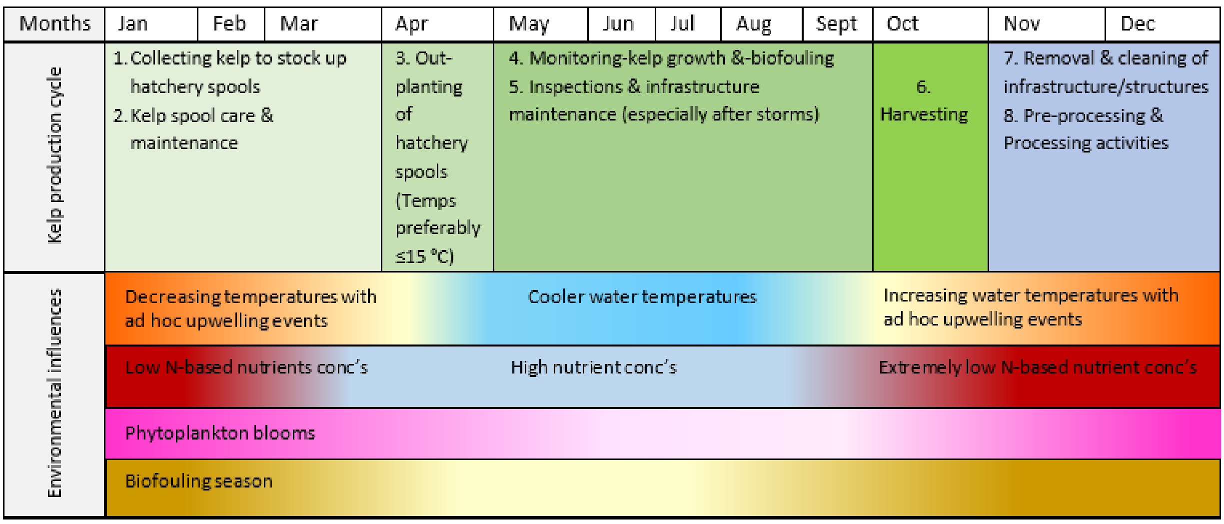


Figure 3: General timeline of the kelp production cycle together with environmental parameters in Small Bay of Saldanha Bay (Diagram credit: Dr Lizeth Botes)

~ In terms of collection of fertile material:

Although it may be the case that collection of sori material for different kelp species elsewhere in the world are only available during certain months of the year, to date we have been collecting sorus material of all three local species throughout the year and have had successful sporulation. That said, it should be noted that there may be variation in quality of spore-producing sorus, either seasonally and/or over a low-tide cycle. Care should be taken in collecting sorus material from kelps, particularly on a spring low-tide period with high air temperatures, as the sori may have already released many of their spores.

~ In terms of the production stages:

It is important to establish the time necessary for each of the three target species in the hatchery and the time available to grow the target species out at sea. While the risk for contamination increases if sporophytes are left too long in the hatchery/nursery, the high level of sedimentation and biofouling in Saldanha Bay may prevent the sporophytes from photosynthesizing if out-planted too small, even if the sporophytes have self-cleaning mechanisms. In Small Bay, we found the best approach is to run the hatchery and nursery between January and March in order to out-plant by the end of March when sea water temperatures drop below 15 °C. In areas more exposed to the open ocean on the west coast of SA, average water temperatures may well be cooler in summer than in winter (with consequent higher nutrient levels) due to upwelling, resulting in out-plantings during different times of the year than mentioned above.

Although our grow-out site at BOM was closely situated to the mouth of Saldanha Bay, Small Bay is very sheltered with little water flow/circulation during summer resulting in minimal nutrient influx between October and December and therefore it is suggested that after the sporophytes remained in weaning for 2 - 3 weeks, that the kelps are grown from April to September until big enough to be harvested by late September or early October. From the data that we have collected to date, it appears that for future kelp farmers wanting to farm with horizontal rope structures, their main rope-line may have to be between 2 - 4 m during winter, while dropping the depth of the main-line to 6 m (if possible) when heading toward late spring where kelps will be within reach of upwelling events. On the vertical dropper rope structures, droppers of ~ 6 m long/deep will likely be a better option and certainly more economical in terms of space.

Once the kelps have been harvested, the rope structures can be removed, cleaned and checked for maintenance between October and December annually. If the farm intends to do its own post-harvesting/pre-processing, these activities can be done during October/November annually or as required by the processor.

~ In terms of nutrients:

Nutrient data (see Annexure 7.3 for more details) shows how dissolved nutrient concentrations slowly decrease towards October with extremely low concentrations during October to December which extends, in the case of nitrate, nitrite and ammonium, into March. This is likely due to the high phytoplankton productivity in Small Bay during this period, certainly creating a challenging environment for kelps to cope with and grow in over that period.

~ In terms of biofouling on kelp blades and phytoplankton present in the bay:

Although phytoplankton and biofouling are present all year round at BOM (see Annexure 7.4 for more details), increased phytoplankton and biofouling over the summer months together with low dissolved nutrient levels provides for a particularly difficult environment for farmed kelps to survive from October to March annually. This will likely not be the case at an open ocean site where more typical upwelling conditions will provide for access to cold nutrient-rich water throughout the upwelling season, which is driven by south-easterly winds from around September to around March annually. While mussel fouling during the 2024 grow-out season was most severe on the grow-out ropes, the mussel fouling during the 2025 grow-out season was not just severe on the grow-out ropes but also on the kelp blades. This will undoubtedly have a major negative impact on the quality of kelp blades and on production costs when attempting to farm with kelps in Saldanha Bay.

Standard Operating Procedures (SOPs) capturing the procedures in the Hatchery, Nursery, Weaning and Grow-out are available on the SA KFP webpage.

6. Conclusions & recommendations

Efforts during Phase 2 of the SA KFP have led to the generation of a significant amount of research in a short period of time to lay the foundations for the potential development of a sustainable kelp farming industry in SA. These efforts include:

- successfully advocating for the amendment of the Environmental Authorisation to include farming of indigenous seaweed species in the Saldanha Bay Aquaculture Development Zone,
- tailoring publicly available hatchery and nursery culturing methods for all three local kelp species,
- trialling various grow-out production systems and obtaining yields on vertical droppers comparable to that obtained in countries such as the USA where kelps are farmed profitably,
- compiling Standard Operating Procedures (SOPs) for the kelp production cycle (hatchery, nursery, weaning, and grow-out methods)
- determining which biofouling species occur on the three species that could possibly affect blade quality and ultimately the price when sold, and the seasonality of biofouling in local kelp aquaculture,
- determining the season most suitable for these kelps to be grown in Small Bay by monitoring and comparing environmental parameters, kelp growth and phytoplankton,
- analysing all three local kelps to determine nutritional content assist with food safety standards and certification,
- conducting preliminary pre-processing trials to establish if two methods of blanching (i.e. boiling and/or steaming) could reduce potentially harmful heavy metals, arsenic and iodine,
- developing a business planning guide for kelp farming in SA and an associated financial forecasting model with worksheets to assist with financial projections and planning,
- and producing a comprehensive kelp market assessment, value chain analysis and roadmap for the expansion and strengthening of the kelp value chain in SA to enable the development of an environmentally and financially sustainable kelp farming industry in SA.

While the research (reports available in the Annexures) and tools (Business Planning guide, Financial forecasting worksheets, SOPs, as well as the Value Chain Analysis, Market assessment & Roadmap for the development of a sustainable kelp farming industry in SA) developed in this project will significantly assist investors and those interested in kelp farming to de-risk and plan new kelp farming ventures, significant hurdles do still remain regarding profitability and overall business viability, especially when considering the degree of mussel fouling pressure in Small Bay and the transition from an experimental small-scale manually focused operation (as was done in Phase 2 of this project) to larger more automated commercially focused operations (as is done elsewhere in other parts of the world). This transition is essential for scaling up in order to compete with global practices.

Additionally, the research conducted during Phase 2 helped to clarify remaining knowledge gaps and unknowns (as outlined below) that require further research. It is therefore recommended that these knowledge gaps and unknowns be addressed in follow-up projects in areas as identified in the Phase 1 Pre-feasibility study to ensure scalability and eventual profitability. Since these sites will each have its own hydrodynamic characteristics and environmental factors that will influence the growth of kelps when grown on farming structures, it is not possible to suggest a blanket approach that could be applied across the board, thus each project will have to consider which component(s) they would like to address, depending on available expertise and financial support. The knowledge gaps and unknowns referred to above, include (but are not limited to):

Knowledge gaps wrt hatchery/nursery:

1. Will there be enough kelp grow-out initiatives requiring spools to allow for a kelp hatchery to operate sustainably?
2. Will there be enough kelp grow-out initiatives to justify a kelp breeding programme to ensure good genetic material to improve yields and environmental tolerance?
3. What change in techniques/systems will be required to culture gametophytes in a breeding programme, as opposed to wild collection of sorus material which are sporulated to grow gametophytes and eventually sporophytes.
4. What culturing methods can be implemented to minimise collections of wild kelp sori material, and will such sophisticated methods be justified and financially viable if kelp farming is limited to nearshore areas in SA?

Knowledge gaps wrt weaning/grow-out:

5. How will the three local species fare on the traditional long-line methods used elsewhere?
6. How will the three local species fare in other areas outside of Saldanha Bay with less mussel fouling pressure, and is it possible that *Ecklonia* and *Laminaria* will perform/grow better in areas with more wave exposure?
7. What structures will be able to withstand different wave exposure levels?
8. What structures will allow better growth performance and yield?
9. While it has been demonstrated that kelp farming contributes to the increase of the biodiversity of smaller marine life, further consideration should be given as to what grow-out structures could be designed that is not harmful to bigger species such as marine mammals?
10. Will more than one harvest per growth season be possible with any of the three local species and in other sites with less mussel fouling?
11. Can biofouling be reduced with better site selection?
12. Will the conditions and water space in Small Bay hinder the possibility of scaling up when more commercially viable grow-out solutions are implemented?
13. How will interaction between kelp farming and phytoplankton affect mussel and oyster farming?
14. Is it possible, in the South African context, to supply consistent quantities of good quality kelp to retain relevant market segments?
15. Can the kelps be produced in a profitable manner and can it compete with the price of wild harvested kelps?
16. What grow-out techniques will be required to farm with kelps in other areas as identified in the Phase 1 Pre-feasibility study?
17. What is the biofouling pressure in other areas as identified in the Phase 1 Pre-feasibility study?

Knowledge gaps wrt harvesting & processing:

18. Which harvesting technologies will be implemented, is the appropriate equipment available locally or will it have to be imported, and how will this affect production cost and a potential kelp farmer's ability to compete with wild harvested kelps?
19. Will the harvesting technology be able to deal with the biofouling pressure in Small Bay and elsewhere?
20. What post-harvesting steps and pre-processing steps will be required to satisfy market requirements and food safety requirements?
21. What pre-processing and processing activities (i.e. fermentation, drying etc) are required to assist with storage of kelp that is harvested seasonally?
22. What processing techniques will be implemented and is the appropriate equipment available locally or will it have to be imported?

Knowledge gaps wrt food safety:

23. What are the next steps for setting food safety standards?
24. How long will the local process for kelp/seaweed food safety standards take and what impact will it have on the use of kelps/seaweeds in animal feed, human food, pharmaceuticals etc.
25. What monitoring and testing will be required for kelp/seaweed farming and what will the cost be?
26. What processing techniques/methods can be used to reduce the concentration of various harmful substances?

Knowledge gaps wrt product development to create demand:

27. How can enough demand be created and increased to enable demand-driven farming? What marketing and awareness creation efforts will be required to create demand locally and/or internationally?
28. If demand-driven farming is possible, what will these products be? And how will this influence research in product development?
29. Can further value-added products (apart from biostimulants and fertilisers) be made feasible to enhance economic sustainability of local kelp aquaculture?

Knowledge gaps wrt access and linkages with markets (locally and internationally):

30. How can potential logistical constraints (such as cold chain facilities, shipping efficiency, or export/import regulatory bottlenecks) affect market access?
31. What processes will be required to stabilise biomass for transport needs to markets?
32. What initiatives will be required to enable access to local and international markets?
33. Can local and international markets be generated for cultivated *M. pyrifera* and *L. pallida*?

The above-mentioned knowledge gaps and unknowns provide guidance for future research and/or follow-up projects which is essential for ensuring the long-term success and financial viability of any future kelp farming business in SA. When the gaps have been addressed, and the technologies provide reliable and commercially viable proof-of-concept, then the roadmap strategies (as captured in the Kelp Value Chain Analysis and Market Assessment study) should be implemented to develop a sustainable kelp farming industry in SA.

7. Acknowledgements

The tireless dedication and hard work of the South African Kelp Farming Project (SA KFP) team, under the direction of the Project Manager, Dr Lizeth Botes, are greatly appreciated. On behalf of the project team, we extend our sincere gratitude to all individuals and organisations who have contributed in one way or another to the success of the SA KFP, your expertise has contributed to laying the foundations for the potential development of a sustainable kelp farming industry in SA.

We are particularly appreciative to the Bivalve Farmers' Association of South Africa (BSASA), under the chairpersonship of Mr Vos Pienaar, for facilitating support from our industry partners Blue Ocean Mussels (BOM) and Paternoster Oyster Company (POC) who provided access to their sites and facilities, and Imbaza Mussels and Blue Sapphire Pearls who provided the project with boat and crew support throughout this project. We also extend our gratitude to Seawise Marine for providing access to the BSASA phytoplankton monitoring data.

Similarly, we wish to thank the Department of Forestry, Fisheries and the Environment (DFFE)'s Directorate of Aquaculture Innovation and Technology Development, under the leadership of Ms Andrea Bernatzeder for strategic advice and providing access to scientific expertise and facilities at the Sea Point Aquaculture Research Facility; and the DFFE Seaweed Research Unit for technical assistance to the Research Assistants when setting up their respective project research components.

We appreciate the collaboration with the University of Cape Town (UCT) and the University of the Western Cape (UWC) who provided access to their facilities that enabled the project students to further their studies. We are deeply grateful to the staff of the Marine Biogeochemistry Laboratory in the Department of Oceanography at UCT for analysing the project's nutrient samples.

We wish to extend our sincere gratitude to the USA National Seaweed Hub, led by Connecticut Sea Grant (via the University of Connecticut) for generously allowing us access to their resources in order to adapt the Kelp Business Planning Guide & Kelp Financial Forecasting Model to a South African context.

We extend our sincere appreciation to the Phycological Society of Southern Africa (PSSA) for hosting the SA KFP's webpage containing the deliverables and outputs of the SA KFP to ensure open access to all interested parties.

The external consultants (namely Ecosense, Advance Africa Management Services, Nautilus Growth Partners and Biosolutiones Technicas) are thanked for their contributions, your willingness to share your expertise greatly contributed to the success of the project.

Lastly, and most importantly, our deepest appreciation goes to the Foreign Commonwealth and Development Office's (FCDO) Southern Africa Research and Innovation Hub (SARIH), under the d project stewardship of Ms Kristin Klose and Nyameka Mbete, for the invaluable funding support from the UK government which were critical to initiating and sustaining this project (both Phase 1 and Phase 2). This ambitious endeavour would not have been possible without the continued support throughout this project.

8. Annexures

7.1 Letter from the DFFE regarding the amendment of the EA

forestry, fisheries
& the environment

Department:
Forestry, Fisheries and the Environment
REPUBLIC OF SOUTH AFRICA

Private Bag X 447· PRETORIA 0001· Environment House 473 Steve Biko Road, Arcadia· PRETORIA

DFFE Reference: 14/12/16/3/3/1/1728/AM3
Enquiries: Ms Thulisile Nyalunga
Telephone: (012) 399 9405 **E-mail:** Tnyalunga@dffe.gov.za

Mr Asanda Njobeni
Department of Agriculture, Forestry and Fisheries
Sustainable Aquaculture Management
Private Bag X2
VLAEBERG
8001

Telephone Number:	021 402 3065
Cell phone Number:	082 924 0101
Email Address:	ANjobeni@dffe.gov.za

PER MAIL / EMAIL

Dear Mr Njobeni

AMENDMENT OF THE ENVIRONMENTAL AUTHORISATION ISSUED ON 08 JANUARY 2018 FOR THE SEA BASED AQUACULTURE DEVELOPMENT ZONE (ADZ) IN SALDANHA BAY WITHIN SALDANHA BAY LOCAL MUNICIPALITY, WESTERN CAPE PROVINCE

The Environmental Authorisation (EA) issued for the above-mentioned application by this Department on 08 January 2018, the amendments dated 10 July 2019 and 16 September 2020, your application for amendment of the EA received by the Department on 27 March 2024, and the acknowledgement letter dated 10 April 2024, refer.

Based on a review of the reason for requesting an amendment to the above EA, this Department, in terms of Chapter 5 of the Environmental Impact Assessment Regulations, 2014 as amended, has decided to amend the EA dated 08 January 2018 as amended, as follows:

Amendment 1: List of approved species on page 7 of the EA

From:
Seaweed: Gracilaria gracilis

To:
Indigenous seaweed species

Amendment 2: Condition 16 on page 13 of the EA

From:
The AMC must be consulted before the appointment of the project ECO, to ensure that they are suitably qualified and have the relevant expertise to monitor and ensure compliance with the conditions of the EA and EMPr.

To:
The AMC must review and provide input into the specifications for the appointment of the project ECO, to ensure that a suitably qualified ECO who has the relevant expertise is appointed to monitor and ensure compliance with the conditions of the EA and EMPr.

The reason for the amendment is as follows:
The removal of the specific reference to the seaweed species *Gracilaria gracilis* and replacement with the words "indigenous seaweed species" the current reference to only one specific indigenous seaweed species (i.e. *Gracilaria gracilis*) is restrictive and prevents the ADZ from farming other indigenous species common to the area such as Kelp and future indigenous species as the market determines.

Seaweed farming was assessed during the EIA process and *Gracilaria gracilis* was put forward at the time as the only seaweed species that had been farmed in the area in the past as an aquaculture species. The market and environment have changed, as the industry has since shown interest in farming other indigenous seaweed species within the ADZ.

General
This EA amendment letter must be read in conjunction with the EA dated 08 January 2018, as amended.

In terms of the Promotion of Administrative Justice Act, 2000 (Act No 3 of 2000), you are entitled to the right to fair, lawful, and reasonable administrative action; and to written reasons for administrative action that affects you negatively. Further, your attention is drawn to the provisions of the Protection of Personal Information Act, 2013 (Act no. 4 of 2013) which stipulate that the Department should conduct itself in a responsible manner when collecting, processing, storing, and sharing an individual or another entity's personal information by holding the Department accountable should the Department abuse or compromise your personal information in any way.

In terms of Regulation 4(2) of the Environmental Impact Assessment Regulations, 2014, as amended (the EIA Regulations), you are instructed to notify all registered interested and affected parties, in writing and within **14** (fourteen) days of the date of the EA, of the Department's as well as the provisions regarding the submission of appeals that are contained in the Regulations.

Your attention is drawn to Chapter 2 of the National Environmental Management Act, 1998 (Act No. 107 of 1998) National Appeal Regulations published under Government Notice R993 in Government Gazette No. 38303 dated 08 December 2014 (National Appeal Regulations, 2014), which prescribes the appeal procedure to be followed. Kindly include a copy of this document (National Appeal Regulations, 2014) with the letter of notification to interested and affected parties in this matter.

Should any person wish to lodge an appeal against this decision, he/she must submit the appeal to the appeal administrator, and a copy of the appeal to the applicant, any registered interested and affected party, and any organ of state with interest in the matter within 20 days from the date that the notification of the decision was sent to the registered interested and affected parties by the applicant; or the date that the notification of the decision was sent to the applicant by the Department, whichever is applicable.

Appeals must be submitted in writing in the prescribed form to:

The Director: Appeals and Legal Review of this Department at the below mentioned addresses.

By email: appeals@dffe.gov.za

By hand: Environment House
473 Steve Biko

MJ

Arcadia
Pretoria
0083 or

By post: Private Bag X447
Pretoria
0001

Please note that in terms of Section 43(7) of the National Environmental Management Act, Act No. 107 of 1998, as amended, the lodging of an appeal will suspend the environmental authorisation, or any provision or condition attached thereto. In the instance where an appeal is lodged, you may not commence with the activity until such time that the appeal is finalised.

To obtain the prescribed appeal form and for guidance on the submission of appeals, please visit the Department's website at https://www.environment.gov.za/documents/forms#legal_authorisations or request a copy of the documents at appeals@dffe.gov.za.

Yours faithfully

Mr Sabelo Malaza
Chief Director: Integrated Environmental Authorisations
Department of Forestry, Fisheries and Environment
Date: 08/05/2024

MS

7.2 Hatchery and Nursery Report – compiled by JJ Bolton

SOUTH AFRICAN KELP FARMING PROJECT (SA KFP)

PROJECT REPORT ON THE HATCHERY AND NURSERY COMPONENT


Photo credit: Lizeth Botes

Report compiled by: Prof Emeritus John J Bolton (Senior Research Scholar, Department of Biological Sciences, University of Cape Town).

Contributors: Dr Lizeth Botes, Dr Brett M Macey, Mr Musadiq Schalkwyk & Ms Frances Hill.

BACKGROUND

Different species of kelps have different environmental requirements and thus require different conditions for optimal development and growth. Of the three local west coast kelp species trialled in this project, two of them (*Ecklonia maxima* and *Laminaria pallida*) have distributions largely limited to southern Africa and have never been grown using commercial procedures (hatchery, nursery, weaning, grow-out) before. The other species (*Macrocystis pyrifera*) is much more globally widespread and has been grown in other continents, especially in Chile, but there have been no growth studies on South African genetic material, which is likely to have somewhat different ecological characteristics judging by its local form and distribution.

Kelps are grown initially from microscopic spores, which are very tiny swimming single cells only about 5 microns (thousandths of a millimetre) long. Kelps produce vast numbers of them, which need to settle on a solid substratum where they develop first into microscopic gametophytes. The microscopic female and male gametophytes produce eggs and sperm respectively and when the eggs are fertilised, the resulting cells grow into small microscopic kelp sporophytes (juvenile kelps) – see Figure 1.

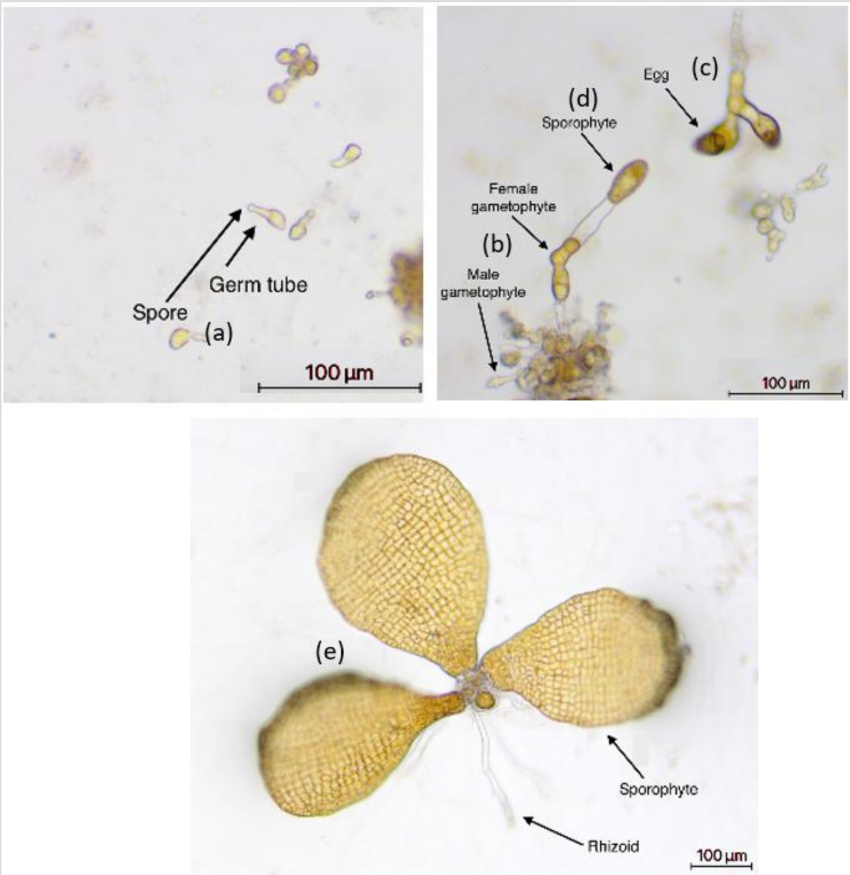


Figure 1. Kelp development during the first few weeks (a) Spore with germination tube leading to the first cell of gametophytes. (b) Female and male gametophytes. (c) Egg released from the female gametophyte, becoming a (d) sporophyte after fertilisation. (e) Juvenile sporophytes producing rhizoids for attachment (Photo credit: Ms F Hill).

The juvenile kelps need to be grown for several weeks into visible plants of a few mm to 1 cm long before they are robust enough to be transferred to the sea for grow-out. The timing of these growth phases depends on the species of kelp, environmental conditions and the optimisation of the hatchery facilities.

What is a hatchery and why is it needed?

In nature, kelps grow on rocks in shallow seas where there is sufficient light for photosynthesis, and very few of the juvenile sporophytes produced, survive to replace adult kelps in the kelp forest. Each adult *E. maxima* kelp plant can produce around 30 billion spores per year. The aim of using a land-based hatchery to initiate kelp farming is to nurture the juvenile kelp sporophytes initially under optimised environmental conditions to enable survival of many more juvenile sporophytes, eventually producing a dense, single-species kelp crop for harvest.

A hatchery consists of a closed room which is capable of temperature control, with surfaces/benches which are capable of thorough cleaning/sterilisation to minimise contamination with other marine organisms (particularly microalgae, marine bacteria and small species of other seaweeds). Small stages of kelps housed in tanks are given excess nutrients via nutrient media, optimal light conditions and as they grow older aeration/water movement to optimise uptake of nutrients and dissolved gases by the juvenile sporophytes. Sterile conditions (including sterilised seawater) are maintained wherever possible to minimise contaminants, which are present on any material brought from the sea. Growth of one major group of potential contaminants, a ubiquitous group of microscopic algae known as diatoms, can be reduced by the addition of a specific concentration of germanium dioxide ($Ge0_2$) in the early stages of growth.

The substrate on which kelps are grown also needs to be optimised, and of a nature which allows easy eventual transfer onto rope structures in the sea for grow-out. Hatchery twine ('seeding string') is required and this is wound around sections of PVC piping ('spool') and after seeding it with spores the spool seeding string is incubated in jars in the hatchery (see SOP 1). When small sporophytes are produced and reach a required level of development (length) several spools are placed in each of several tanks (Figure 2), which enables better environmental conditions for the growing kelps, particularly light and water flow.

Figure 2. The hatchery at POC with spools in cultivation tanks, and trays with kelp blades in front of canisters (Photo credit: Dr L Botes)

Collection and selection of kelp fertile material (sorus)

Different kelp species produce slightly raised areas of tissue on different parts of the plant, which are known as sori (singular: sorus). These patches contain the structures which release spores. The three local species have fertile areas of blade on different parts of the plant: in *L. pallida* on areas of the main split single blade, in *E. maxima* on secondary lateral blades, and in *M. pyrifera* on small blades without floats attached at the base of the plant (see Figure 3 and SOP 2).

Ecklonia maxima *Laminaria pallida* *Macrocystis pyrifera*

Figure 3. Pictures of sorus on blades of the three species, best visible when held up against the light (Photo credit: Ms F Hill)

Most kelp species around the world grow in temperate regions, with large differences in conditions between summer and winter, and many kelp species only have fertile material at certain times of the year (often late winter into spring). In contrast, all three South African west coast kelps have some fertile material all year round. Nevertheless, the available data suggest that there is a large seasonal pattern in production of fertile material. In the only local species studied in detail, *E. maxima*, fertile material per plant showed a minimum in late summer and then a steady increase until a peak in spring. Spore release per unit fertile area also varies seasonally, low in late summer/winter and highest in spring/early summer. So, it may be possible to produce juvenile local kelps from spores all year round, but success may depend on production of large numbers of healthy spores, as well as optimal conditions for out-planting several weeks after spore settlement.

Clean sorus material is selected (free of visible growth of small seaweeds, microalgae and marine animals) during collection and wiped to remove invisible fouling. Collection should be during a low spring tide, and as deep as feasible, as a previous low tide may have stimulated spore release in the shallowest kelps, leaving few healthy spores left to be released. Collection should be rapid with no sorus material allowed to partially dry out.

Methods and conditions for sorus collection need to be optimised for sorus transport, in order to maintain sorus condition without spore release until required. Sorus is transported damp but not wet, kept cool and transport time kept to a minimum. The damp sorus is stored in a cool, dark place overnight, and then in the morning placed in cool, fresh seawater in light, which stimulates spore release.

Hatchery operation and development

In several countries in the North Atlantic, where kelp aquaculture has been initiated and is developing over the last few years (e.g. USA, Ireland, Scotland), a common industry model is for a central hatchery to supply ‘seeded strings’ (as twine wound around spools) every year to a number of grow-out operations. The development of one or more successful hatcheries is critical to this model. In order to maximise the potential for continuity following the short-term Phase 1 Pre-feasibility study, it was considered essential to set up and operate a hatchery at the only permanent government facility with infrastructure and expertise in aquaculture. For example, continuous running seawater to enable kelp hatchery growth is only available in SA at commercial aquaculture farms and at the DFFE Marine Aquaculture Research Facility in Sea Point. Many marine aquaculture ventures fail because of an inability to provide an uninterrupted supply of good quality seawater for growth. Thus, it was considered critical for the SA KFP to operate two experimental hatcheries to attempt kelp aquaculture in South Africa (SA); one at the DFFE, and the other at a commercial aquaculture facility. In Phase 2 of the project, the latter was initially based at Buffeljags Abalone Farm for the first few months, as the same company (then Viking Aquaculture) also operated an oyster farm in Small Bay of Saldanha Bay. After Viking Aquaculture left the project due to company restructuring, the industry-based hatchery was relocated to Paternoster Oyster Company (POC) on the west coast. The latter are much closer both to a good collecting site for the three species at Jacobsbaai and to the grow-out site in Saldanha Bay, and thus transport of fertile material to POC and seeded strings to Saldanha Bay were minimised.

Because of the existing DFFE facilities and technical support for aquaculture at Sea Point, it was possible to maintain controlled conditions at the DFFE based hatchery where more detailed studies on optimal environmental conditions for growth were conducted in the two project incubators/growth chambers. Thus, at the DFFE based hatchery, more detailed experiments were conducted on our local species, necessary when a species is grown in aquaculture for the first time. The DFFE hatchery also provided material for grow-out, whereas the POC based hatchery conducted growth trials needed in a commercial setting and provided the majority of the seed material to the grow-out site.

FINDINGS OF THE TRIALS CONDUCTED AT THE PROJECT HATCHERIES

At the beginning of Phase 2 (in late 2022), studies on hatchery procedures of the three local species were in their infancy. Through the course of Phase 2, our knowledge of optimal procedures for producing seeded strings for grow-out developed rapidly with increasing success, and with shorter growth periods for kelp early stages as outlined in SOP 1 - 7.

The time between **Nov 2022 - Mar 2023** were utilised to setting up the initial hatchery at the DFFE Marine Aquaculture Research Facility in Sea Point, with an initial industry hatchery constructed at Buffeljags abalone farm. During this time, an initial seeding attempt of kelp juveniles of a few micrometres took place in Dec'22, however this effort was unsuccessful.

During 2023 - 2024, regular seedings began initially every two weeks, however, a series of technical problems slowed progress at the DFFE based hatchery which included electricity load-shedding, contamination problems and various hatchery breakdowns but despite these difficulties, the first successful out-planting of spools from the DFFE based hatchery took place on 11 May'23. With the departure of Viking Aquaculture from the project in the beginning of May'23, a research assistant (Ms Imke Meyer) employed during Phase 1 of the project gained employment at POC on the west coast at Paternoster close to Saldanha Bay, and showed interest in assisting the project with setting up an industry hatchery at POC. Subsequently, the decision was made to relocate the industry hatchery component to POC with the first batch of spools inoculated in Aug'23 (see Figure 4).

Figure 4. POC based hatchery after set-up with the 1st batch of kelp spools (Photo credit: Dr L Botes)

While improvements were being made to the DFFE based hatchery, trials continued in the project incubators, and better monitoring of growth was achieved with the new project microscope (see Figure 5)

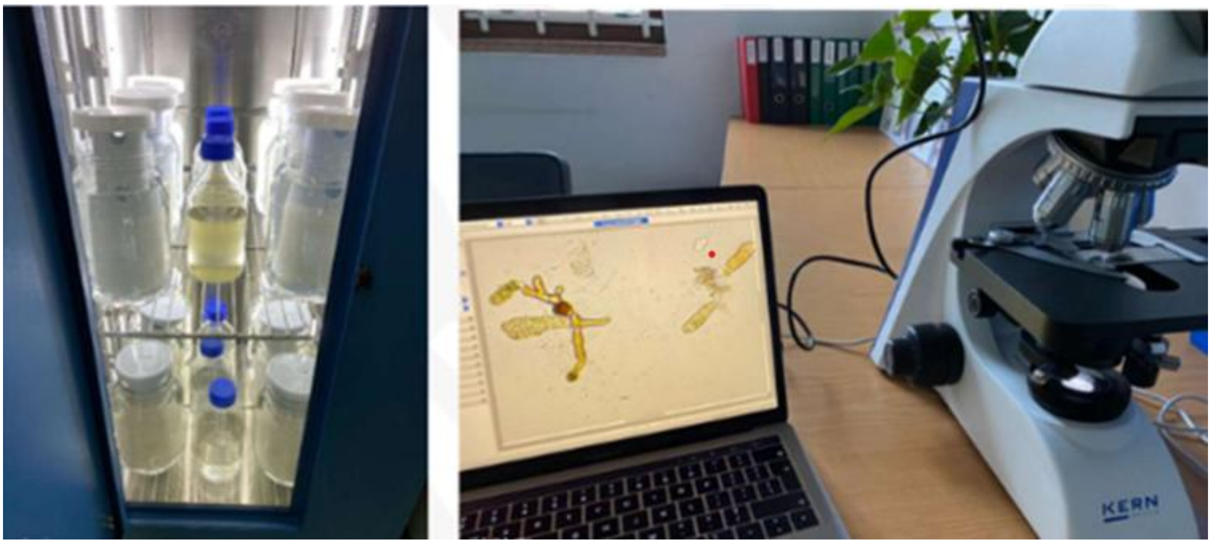


Figure 5. (a) Spools of all 3 species (from Kommetjie and Jacobsbaai) stored in jars in both project incubators and (b) newly settled sporophytes visible under the microscope. (Photo credits: Ms F Hill)

After one month, the juvenile kelps at POC reached approximately 3 mm in length, much faster growth than thus far achieved at the DFFE based hatchery, which took two months to reach the same length. There was some contamination with other organisms and a move towards increased attempts to reduce this (with iodine treatment of sori surface before sporulation and the addition of GeO_2 for diatom reduction after sporulation) was initiated.

Initially the approach was taken to move kelp sporophytes, which are barely visible with the eye, from the hatchery directly to grow-out and immediately out-plant and expose them to the outside environmental elements without intermediary stages. While this approach may well work elsewhere (perhaps in waters with less sedimentation and biofouling), it was found that maintaining the sporophytes for a longer period in a ‘nursery stage’ at POC is more successful in Small Bay as the out-planting site. The inclusion of the nursery stage (where sporophytes were grown to ~1 cm) gives the kelps from the nursery a better chance to compete with sedimentation and biofouling when out-planted in Small Bay, even though we eventually end up having to accept some degree of contamination in the nursery. As such, kelps grown at the two hatcheries (POC & DFFE) were out-planted at various times of the year with varying success (see Annexure 7.3 for more information of the outcomes of these out-plantings), although out-plantings annually from March onward is presumed to be more optimal.

During **2024 - 2025**, upon the departure of Ms Meyer in Mar/Apr'24 who took employment at Seaweedland in the Netherlands, a Project Assistant (PA) namely Mr Musadiq Schalkwyk, was appointed in Jun'24 and trained by the Project Manager (PM) Dr Lizeth Botes, to continue the work at the POC based hatchery and to assist the Research Assistant (RA) Ms Nontobeko Xulu in grow-out at BOM for the remainder of the project. Various trials to compare growth media, temperature and spore concentrations were conducted at the POC based hatchery with recommended changes from the incubator experiments conducted at the DFFE based hatchery (see the next section below), but it was found that the best growth conditions were to use 15°C for all three species, half strength Provasoli's Enriched Seawater (PES) growth medium for all three species, and 2000 spores per ml for *Laminaria* and *Ecklonia*, 5000 spores per ml for *Macrocystis*. Subsequently, additional trials of all three species from the POC and the DFFE based hatcheries were out-planted resulting in harvesting, food safety tests and pre-processing experiments (see Annexures 7.3 and 7.4 dealing with the grow-out and food safety tests respectively for more information).

During the **2025 extension period**, the last and final trial at the POC based hatchery was set-up by the PA and PM with the above-mentioned variables. During this trial, all species reached an average of 1 cm in length within seven weeks (see Figure 6), compared to eight weeks previously, and these were out-planted in mid-Mar'25, to enable a final growth period during the final write up phase of the project.

Based on the data accumulated over the study period, a general timeline for hatchery production was drawn up (see Figure 6).

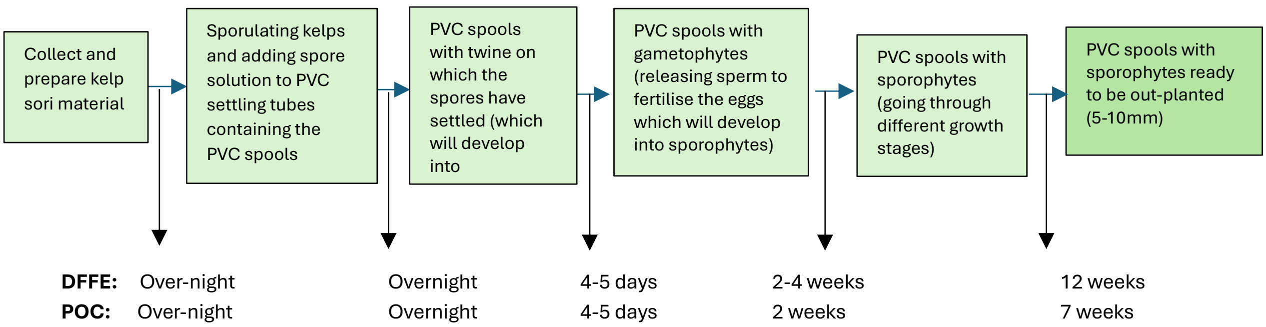


Figure 6. Timeline of all three species from collection of kelp sori to sporophytes ready for out-planting. (Diagram credit: Dr L Botes)

Figure 7 shows a photographical representation of the progress of the developmental stages of all three species up to day 49 at the POC based hatchery, while Figure 8 shows the corresponding graphical comparison between the three species during the gametophyte stage and the sporophyte stage, indicating the rapid increase in sporophyte growth from day 35 up to day 49. Additionally, it also shows that at POC, *L. pallida* already formed sporophytes by day 14 while the other two species were still gametophytes (For more details on the experiments conducted at POC, see the PM's 2024 - 2025 Q2 and Q3 - 4 report).

Figure 7. Developmental stages of (a) *E. maxima*, (b) *L. pallida* and (c) *M. pyrifera* up to day 49 in the POC Hatchery/Nursery (Photo credits: Mr M Schalkwyk)

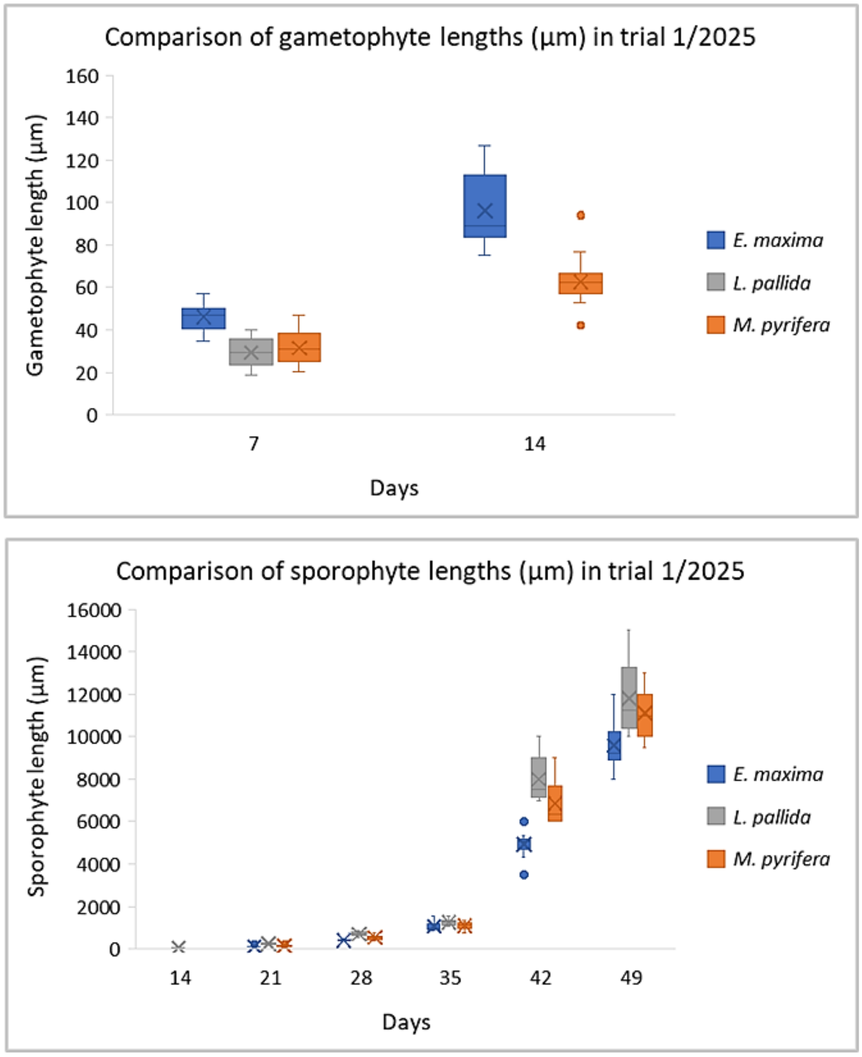
(a)
(b)


Figure 8: Boxplot showing the comparison of the (a) gametophyte lengths and (b) sporophyte lengths of *E. maxima*, *L. pallida* and *M. pyrifera* in trial 1 of 2025 at the POC based hatchery as on 17 Mar'25. **Note 1cm =10 000µm**. The whiskers indicate the maximum and minimum values, the x in the box indicate the mean and the horizontal line in the box indicate the median. n=18 where n is the number of samples measured per species (Graph credit: Mr M Schalkwyk)

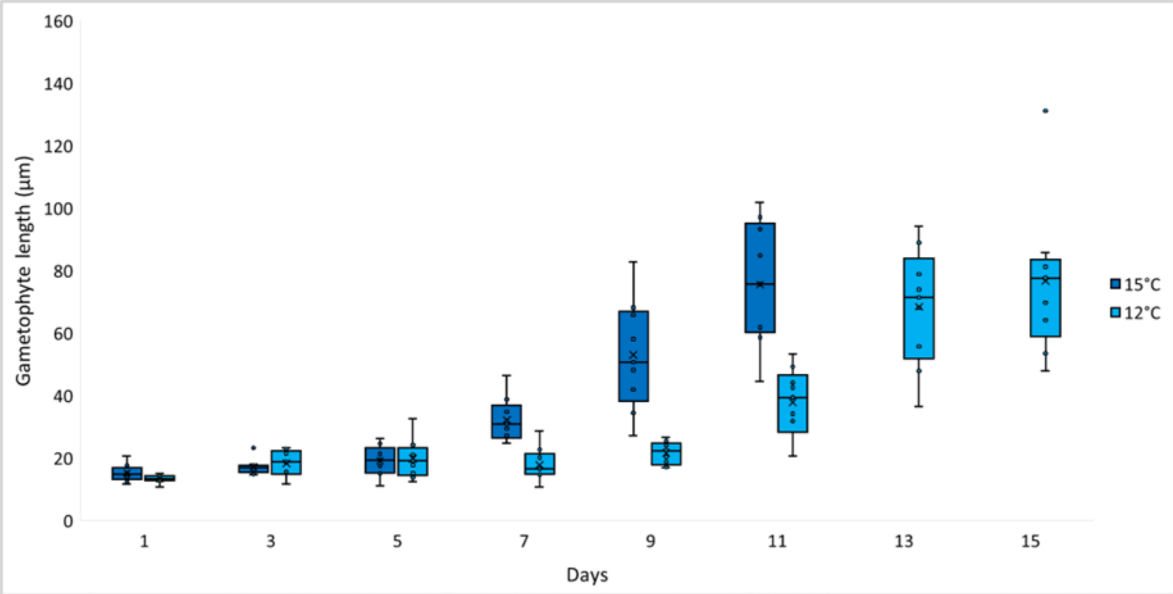
FINDINGS OF THE INCUBATOR EXPERIMENTS CONDUCTED AT THE DFFE BASED HATCHERY

The results from the various trials described above showed that local kelps can be successfully grown in the two hatcheries. However, the kelps were grown and developed under conditions suggested by literature for other kelp species or, in the case of *M. pyrifera*, the same kelp species for other locations in the world (e.g. Chile). These conditions may not be optimal specifically for the South African *E. maxima*, *L. pallida* and *M. pyrifera*. As such, the objective was to identify and test four conditions which could be optimised in the hatchery. These were: optimum temperature, nutrient media type, spore stocking density and light intensity for each of the kelp species. While one parameter was tested, the other three were kept constant.

Variables tested:
Temperature: 12°C and 15°C.
Nutrient media: half strength Provasoli Enriched Seawater (PES) and Guillard (f/2) Enriched Seawater
Spore stocking density: 2000 spores per ml and 5000 spores per ml.
Light irradiance: (30 µmol.$m^{-2}s^{-1}$ and 60 µmol.$m^{-2}s^{-1}$).

The experiments conducted by the RA, Ms F Hill at the DFFE based hatchery, were carried out on microscopic kelp stages obtained from settled spores, growing and developing on microscope slides in crystallising dishes in controlled temperature incubators fitted with dimmable lights. An example of the data obtained from these experiments is provided in Figure 9 (temperature experiment on *E. maxima*).

(a)



(b)

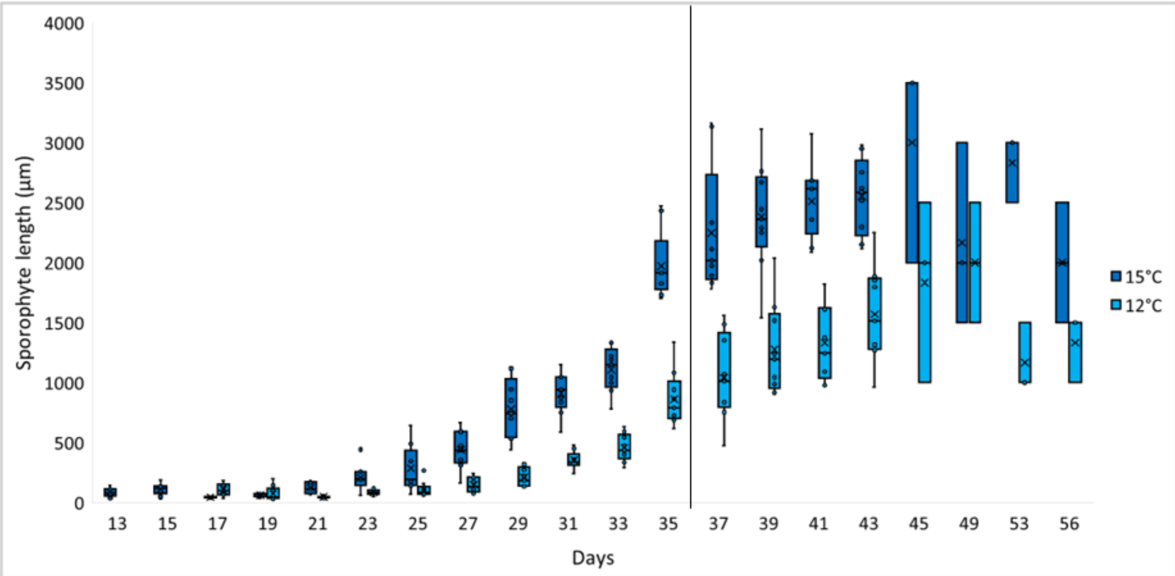


Figure 9. Boxplot showing the length of *E. maxima* (a) gametophytes and (b) sporophytes (b) experiencing different temperature conditions over time while the other variables were kept constant. **Note 1cm =10 000µm** (Graph credit: Ms F Hill).

The results from the temperature experiment showed that, at this scale, all three species can grow and develop successfully at 15 °C. Under 15 °C, *L. pallida* and *M. pyrifera* performed the best in terms of sporophytes reaching 1 mm in average length by day 35 followed by *E. maxima* by day 37. Maintaining seawater temperatures is energetically expensive and having all three species at the same temperature will be more cost effective for aquaculture farmers.

The nutrient media experiment showed that, at this scale, all three species can grow and develop successfully with either nutrient medium. However, although f/2 is readily available on aquaculture farms as it is commonly used as a nutrient medium for microalgae and PES is expensive and time-consuming to prepare, PES is specifically designed for kelp growth and should therefore be used in preference. In PES nutrient medium *E. maxima* performed the best in terms of sporophytes reaching 1 mm in average length by day 33 and *L. pallida* and *M. pyrifera* by day 35.

The results from the spore stocking density experiment suggest that all three species, at this scale, can grow and develop successfully with either 2000 or 5000 spores per ml stocking density. As there are multiple factors which can affect the health of the spores prior to inoculating it is worth ensuring the best possible chances of sporophyte development by ensuring there is a sufficient spore count to produce gametophytes to supply eggs, and sperm for fertilisation. With 5000 spores per ml stocking density respectively *E. maxima* performed the best in terms of sporophytes reaching 1 mm in average length by day 33 followed by *L. pallida* by day 35 and *M. pyrifera* by day 37.

The results from the light irradiance experiment showed that, at this scale, under 60 μmol light intensity conditions *E. maxima* performed the best in terms of sporophytes reaching 1 mm in average length by day 35 followed by *L. pallida* by day 37. Sporophytes did not reach 1 mm in the dishes for *M. pyrifera*. Light is a critical factor in seaweed growth and can be too high or too low for small growth stages. Hatchery managers need to be aware of light levels and the various stages of growth (For more details on these experiments, see Ms F Hill's MSc thesis as listed in the table of Section 4.6 of the main report pp 22 - 23).

SUMMARY OF RECOMMENDATIONS FOR HATCHERY PROTOCOLS

The work carried out over Phase 2 of this project in the two hatcheries (DFFE and POC) has shown that both hatcheries proved capable of producing seeded spools of all three local species of west coast kelps. Nevertheless, as is the case with other initial attempts to cultivate new species in a new environment, there were considerable initial difficulties, and it took several attempts to reach successful production.

As has been suggested elsewhere, it proved very beneficial to have an initial phase in confined containers, where the settled spores develop into gametophytes, and small sporophytes are produced and undergo initial development. This minimises contamination at this early stage. Then a nursery phase is instituted, which places the spools in larger tanks, with water motion to improve uptake of nutrients and dissolved gases. The latter gives more opportunity for contamination with other organisms – this stage is a balance between potential contamination and optimum growth conditions, which must be tested in each hatchery.

Numerous trials, as well as more controlled laboratory experiments in incubators, showed that all species grow well in 15 °C, and it is not necessary to perform the expensive task of reducing the temperature to 12 °C for *M. pyrifera*, as is practiced elsewhere (e.g. Chile). Similarly, various levels of light, spore density, and two commonly used nutrient media were tested on glass slides in crystallising dishes, with little difference between them.

Throughout the project, development of kelps in the hatchery/nursery stages were quicker at POC based hatchery than at the DFFE based hatchery. While it is difficult to be certain of the reasons for this, there are various differences between the two facilities for example, in water supply and treatment and the DFFE based hatchery is also further from collection sites of kelp sorus than POC.

It became clear that there was a benefit at the grow-out stage to produce slightly larger sporophytes on seeded spools in the hatchery to outplant in Small Bay than are recommended in some other facilities overseas. In our systems we found that sporophytes should be around 1 cm in length before proceeding to grow-out, whereas some elsewhere recommend only a few mm. It is possible that conditions in Small Bay are relevant here, with relatively high rates of sedimentation and biofouling, requiring larger sporophytes for early survival.

Detailed procedures and recommendations for hatchery/nursery conditions are included in the SOPs available on the project webpage.

ACKNOWLEDGEMENTS:

The broader project team is thanked for their respective contributions toward this research which has been funded by the UK government through the Foreign, Commonwealth & Development Office (FCDO).

7.3 Weaning and Grow-out Report – compiled by L Botes

SOUTH AFRICAN KELP FARMING PROJECT (SA KFP)

PROJECT REPORT ON THE WEANING AND GROW-OUT COMPONENT

Report compiled by: Dr Lizeth Botes (Project Manager, Sound Interaxions).

Contributors: Mr Musadiq Schalkwyk, Ms Waqeefah Moosa and Ms Nontobeko Xulu.

OBJECTIVE:
This report aims to summarise the findings of the weaning and grow-out component of the project, which includes the kelp farming structures that were trialled and the environmental factors that influenced the growth of the local kelps (*Macrocystis pyrifera*, *Ecklonia maxima* and *Laminaria pallida*) during the study period (2022 - 2025).

SITE DESCRIPTION:
Saldanha Bay (Figure1) is situated on the west coast of South Africa (SA) and forms part of the Southern Benguela Upwelling System. Saldanha Bay is divided into Outer Bay and Inner Bay with the Langebaan Lagoon extending south from Inner Bay. Inner Bay's hydrodynamics has been altered by the construction of a man-made breakwater and iron ore jetty during the 1970s, dividing Inner Bay into Small Bay and Big Bay, each with different hydrographic regimes. Although this has led to variations in productivity and water quality within the bay, the protected environment makes it ideal for mussel and oyster farming and potentially for kelp farming.

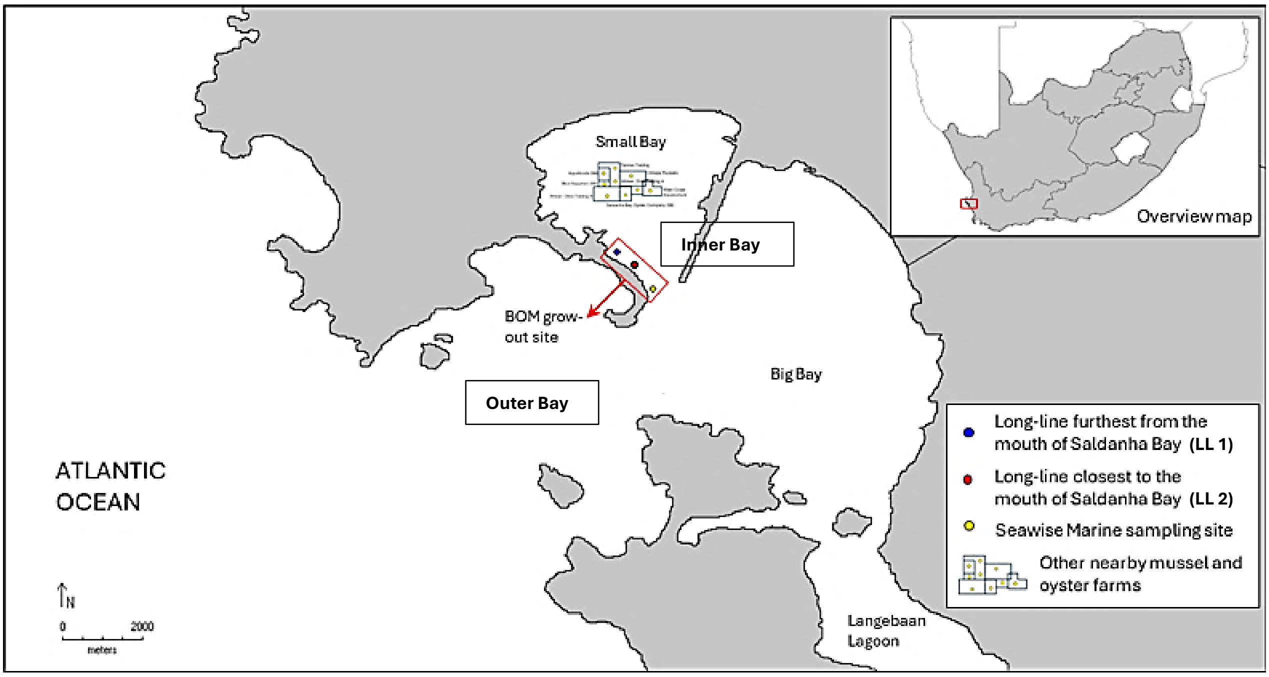


Figure 1. Map of Saldanha Bay indicating the BOM study site within Small Bay (Image credit: Ms W Moosa)

The study site is situated in Saldanha Bay, which was declared as an Aquaculture Development Zone (ADZ) in 2018. The Blue Ocean Mussels (BOM) grow-out site which is approximately 12 m deep was chosen due to its close proximity to the mouth of the bay, providing access to the cold nutrient-rich waters of the Benguela current during the upwelling season (September through to March annually) when south-easterly winds are the primary driver of upwelling on the west coast of SA.

GROW-OUT STRUCTURES TRIALLED:
Two rope structures were trialled during this study (see Figure 2) namely:

(a) rope ladders that were 2 - 5 m wide and 6 m long with ladder rungs at 2 m, 4 m and 6 m suspended from two mussel rafts and two long-lines (with hatchery twine containing juvenile sporophytes which was horizontally unwound onto each ladder rung).

(b) rope droppers that were 6 - 7 m long and suspended 2 m apart from the main long lines (with hatchery twine containing juvenile sporophytes which was vertically unwound down the length of the dropper).

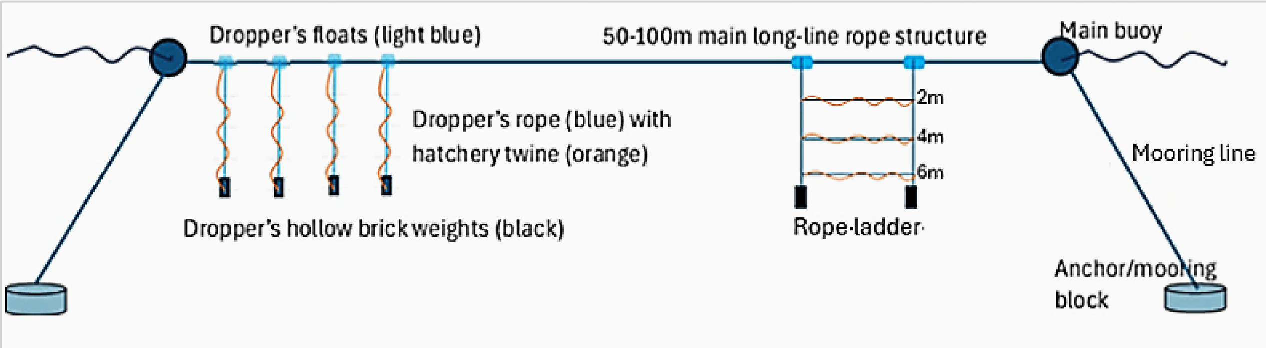


Figure 2. Outline of a rope ladder and rope droppers suspended from the main long-line (Diagram credit: Dr L Botes).

The above mentioned rope structures were positioned at two locations (see Figure 1) namely:

(a) in blue - the position of the mussel raft and long-line further away from the mouth,
(b) in red- the position of the mussel raft and long-line closest to the mouth.

GROW-OUT TRIALS:

The time between Dec'22 to Mar'23 was utilised to establish the project and to obtain the necessary research permits and approvals for the installation of the grow-out structures on which the following grow-out trials were conducted:

(a) 2023 - 2024 grow-out season:
Kelps were out-planted on rope ladder structures suspended from mussel rafts and long-lines.
(b) 2024 - 2025 grow-out season:
Kelps were out-planted on rope ladder structures and rope droppers suspended from long-lines only.
(c) 2025 extension period (Mar'25 - Sep'25)
Kelps were out-planted on vertical rope droppers suspended from long-lines.

ENVIRONMENTAL MONITORING:

The following environmental factors were monitored to determine the best time to grow kelps within Small Bay of Saldanha Bay:

(a) HOBO loggers/sensors were used to do continuous monitoring (from Jul'23 - Sep'25) of temperature, pH and Dissolved Oxygen (DO) at 2 m, 4 m and 6 m depths.
(b) Weekly water samples were collected (from Jul'23 - Mar'25) for analyses of nitrate, nitrite, ammonium, phosphate and silicate concentrations in the water at 2 m, 4 m and 6 m depths.
(c) Phytoplankton samples were collected once a month (from May'24 - Dec'24) at seven depths from 0 - 6 m.
(d) Kelp biofouling samples were collected once a month (from May'24 - Dec'24) at every meter from 1 - 6 m.

FINDINGS:

For the purposes of this report, the outcomes of the various trials will be briefly discussed (more details are available in the Project Manager's quarterly reports available on the project webpage) but the main focus of the discussion will be on what worked. While we have had success with growing the three local kelp species (albeit with varying success depending on the species and grow-out structures), it should be noted that due to limited scale and grow-out time, **we have not yet been able to determine the potential profitability of farming with kelps locally**.

1. <u>Kelp growth and yields obtained</u>
   During the 1st grow-out season, challenges in the hatcheries resulted in only *Macrocystis* and *Laminaria* being out-planted on ladder rope structures (in May'23 and Jul'23 respectively) and grown on both mussel rafts and long-lines. From these trials (outlined in Ms N Xulu's MSc thesis as listed in the table of Section 4.6 of the main report pp 22 - 23), it was evident that *Macrocystis* grew the fastest with enough biomass available for the first batch of *Macrocystis* to be sent for food safety tests and nutritional analyses by Oct'23 (for more information on these results see Annexure 7.4). Although the blades of *Laminaria* reached up to 50 cm, there was not enough biomass for food safety tests and nutritional analyses. Additional trials were out-planted later in the year, and specimens of both species were left on the rope structures to determine if the kelps would survive throughout summer and if enough cold nutrient rich water would be pushed into the bay during the upwelling season to sustain growth. Although the kelps at 6 m initially survived due to occasional upwelling, the blades of both species on all depths either deteriorated over the summer or became completely overgrown with biofouling. It was evident that the kelps that grew on the ladders suspended from the mussel rafts in close proximity to the mussel droppers, were in a much worse state than those that were suspended from the long-lines (which were further away from mussel rafts) likely due to the kelps being damaged by the adjacent mussel droppers on the mussel rafts or perhaps having less water movement and light due while being suspended from the mussel rafts .

   During the 2nd grow-out season, all three kelp species were out-planted (though at different times of the year as material was made available from the hatcheries) on ladders and droppers, but this time suspended from long-lines only. In Jan'24, *Macrocystis* and *Ecklonia* were out-planted on the rope ladder structures suspended from long-lines. The Project Manager (PM) Dr Lizeth Botes then proposed the introduction of droppers suspended from long-lines, but to instead hang the *Macrocystis* spools in 'weaning' (see SOP 10) for a few weeks at the end of Jan'24 prior to unwinding them in early Feb'24 onto droppers. On the ladder rope structures, a significant amount of biofouling started to accumulate with *Ecklonia* reaching up to 60 cm in length and *Macrocystis* reaching ~1.6 m by Mar'24, however soon thereafter *Ecklonia* deteriorated and was not able to rid itself from the increasing biofouling. Even *Macrocystis* was eventually covered with biofouling. On the contrary, the growth of the *Macrocystis* on the droppers far outpaced that of the *Macrocystis* on the ladders, reaching over 2 m in length by Mar'24 with noticeably less biofouling present on the droppers than on the ladders.

   An interesting observation was that the blades of *Macrocystis* were generally broader on the ladders than on the droppers, which is a morphological adaptation where blades become broader when there is less water movement, while the blades are more slender when there is more water movement. Due to the large difference in growth between the ladders and droppers, additional droppers were added later in the year containing *Laminaria* (out-planted in late Apr'24 and unwound in early May'24) and *Ecklonia* (out-planted in late Aug'24 and unwound in early Sep'24).

   Earlier in the grow-out season, it seemed that the kelps between 2 - 4 m were performing best but by the end of Sep'24, the vertical growth profile of the kelps on the 7 m droppers showed that the bulk of the biomass was situated between 1 - 6 m for both *Macrocystis* (wet weight 26.55 kg per 7 m dropper) and *Laminaria* (wet weight 12.28 kg per 7 m dropper) – see Figures 3 and 5. The kelps of both species were subsequently harvested and sent for food safety tests and nutritional analyses (for more information on these results see Annexure 7.4).

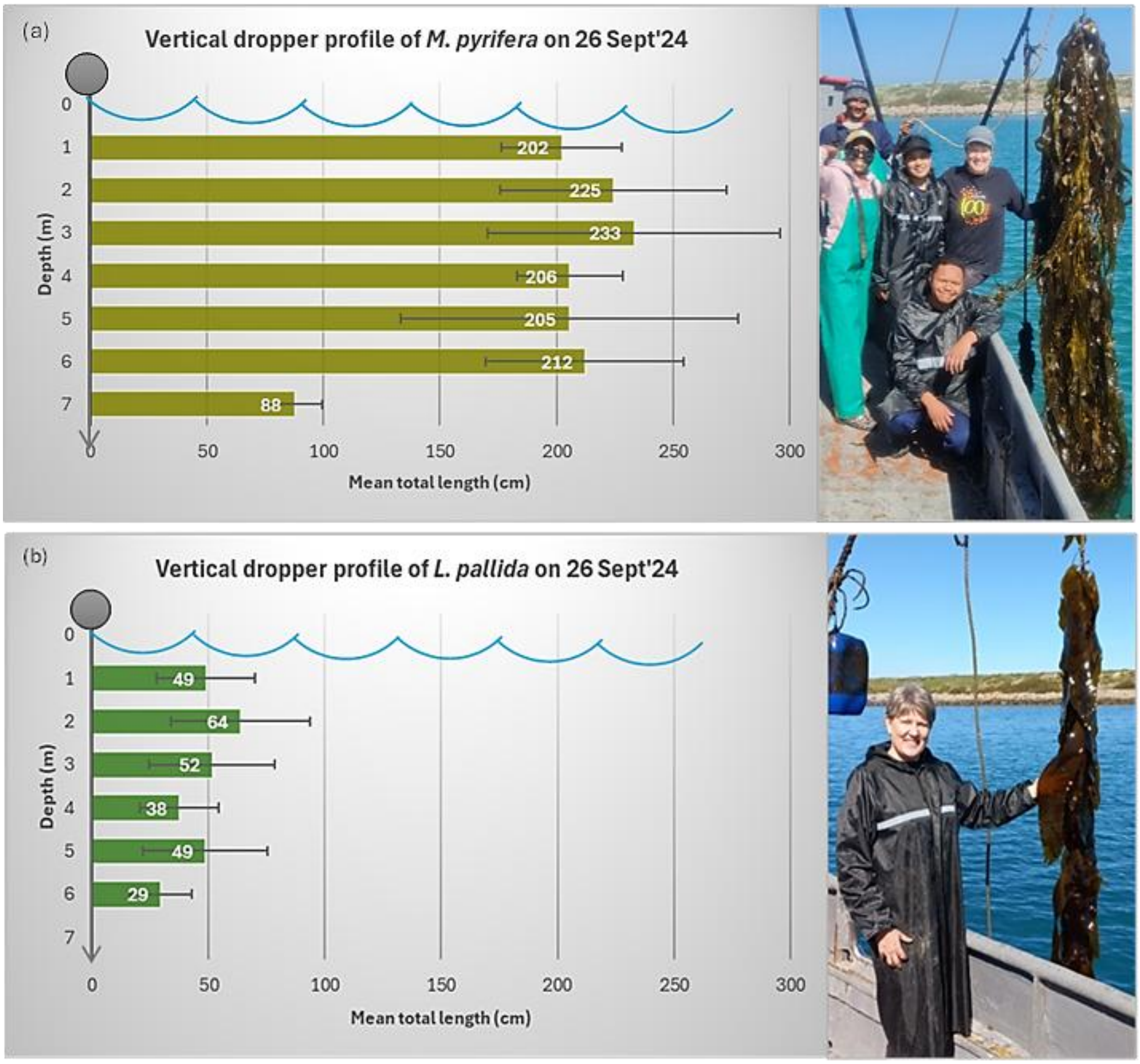


Figure 3. Vertical profile of the mean total length of (a) *M. pyrifera* after **8 months** and (b) *L. pallida* after **6 months**. Standard error bars indicate the spread of the data around the mean value. n=6 where n is the number of specimens counted at each depth. (Graph credits: Dr L Botes, Photo credits: Mr C Cloete and Prof JJ Bolton)

Using these values, if 65 droppers are attached onto a 100 m long-line it would amount to just short of 2 tonnes in the case of *M. pyrifera* and just short of 1 tonne in the case of *L. pallida*. This is comparable to the yields obtained with *Saccharina latissima* (~10 kg/m thus 1 t/100 m long-line) which is being farmed profitably in the USA.

By Oct'24, the 2 cm *Ecklonia* (Figure 4 a, b) that was out-planted in Aug'24 and unwound in Sep'24 grew to 6 cm but was totally overgrown with hydroids by Oct'24 (Figure 4 c). Although the specimens deeper down in the water column in reach of the occasional upwelling events, survived a bit longer, none of the kelps survived the warmer nutrient depleted waters in the upper layers during the latter part of the year.

Figure 4. (a & b) 2 cm *E. maxima* in weaning before being unwound onto droppers on 30 Aug 2024 (c) 6 cm *E. maxima* covered with hydroids on 3 Oct'24 (Photo credits: Ms L Mansfield, Ms N Xulu and Dr L Botes).

Kelp blades can be used for various products (i.e. for human consumption, animal consumption, biostimulants etc.) and therefore each product will have different quality requirements. For this reason, and the fact that abalone prefer the blades to the stipes and floats, we have separated

(a) in the case of *M. pyrifera*, the fouled areas from the rest of the unfouled parts of the blades as well as the stipes and the floats.
(b) in the case of *L. pallida*, the fouled areas from the rest of the unfouled parts of the blades.

When looking at the wet weight of the various components of the kelps, Figure 5 needs to be interpreted with the following in mind; apart from the natural blade losses during the winter storms:

(a) there was a time delay of one week between when the mean total lengths were measured (presented in Figure 3) and when the wet weights were determined (presented in Figure 5), which impacted the yield and the quality. In future, when determining when to harvest, it should be considered that hydroids could settle onto the blades within one week as the water starts warming.
(b) in the case of the *L. pallida* dropper, the density of the kelps on the dropper was also influenced by the density on the spools coming from hatchery in that *L. pallida* (at both hatcheries) started falling off if kept longer than 50 days in the hatchery. In future, this should be considered as it would greatly impact yields in grow-out.
(c) in the case of *M. pyrifera*, blade samples for assessing biofouling were collected monthly from May'24. This entails cutting the older blades off at the blade's float while leaving the growth tip intact to allow the plant to continue growing. Thus, while the total mean length increased (as observed in Figure 3), the yield presented in Figure 5a decreased.

The harvest on 3 Oct'24 demonstrated that for both kelps, less than 30 % of the total wet weight consisted of fouled material (see orange bars in Figure 5 a & b). Depending on the type of product, this may or may not negatively impact profits and can be minimised if harvest time and product readiness are appropriately monitored. In the case of *M. pyrifera* (see Figure 5 a), a very small amount of wet weight is attributed to stipes (9.9 %) and floats (5.3 %), but again even this may or may not affect yields/profits depending on the future of product innovation especially if companies consider a zero-waste approach. The yields from this grow-out season were mainly used for assessing biofouling on the blades and for food safety tests and nutritional analyses.

It should be said that the mussel fouling pressure on the grow-out ropes (regardless of it being a rope ladder or rope dropper on a mussel raft or a long-line) was significant and will undoubtedly increase production costs when having to clean and separate the mussels from the grow-out ropes. This is unfortunate, as a potential kelp farming industry already has pressure to compete with wild harvested/collected kelp industry where the input costs are significantly lower.

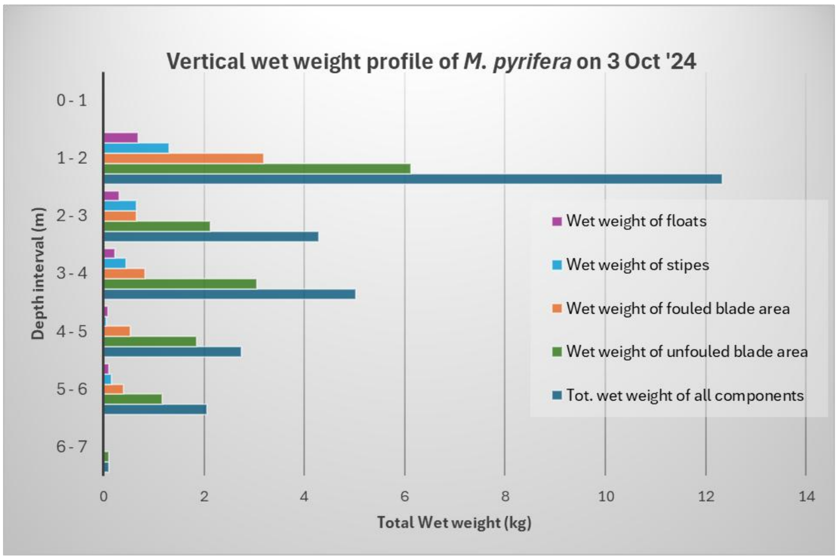


Figure 5 (a). Wet weight profile of the different components of the *M. pyrifera* dropper on 3 Oct'24 (Graph credit: Dr L Botes)

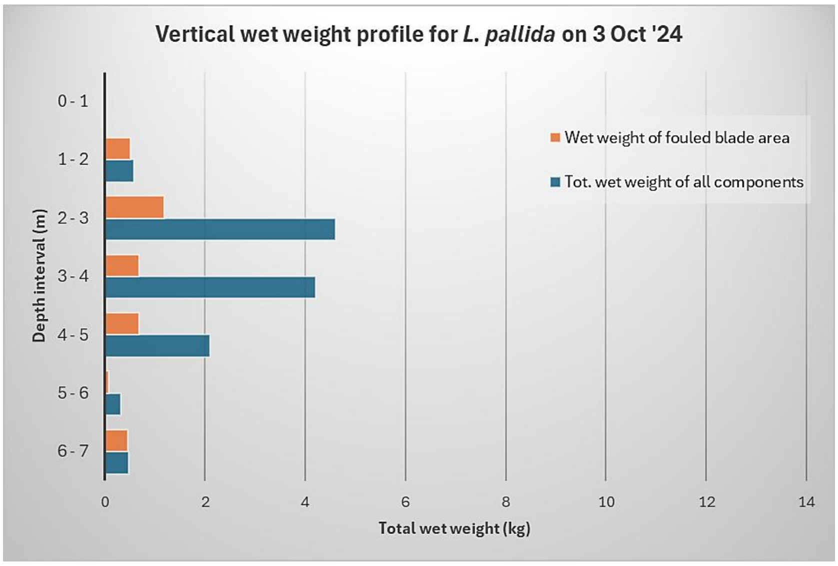
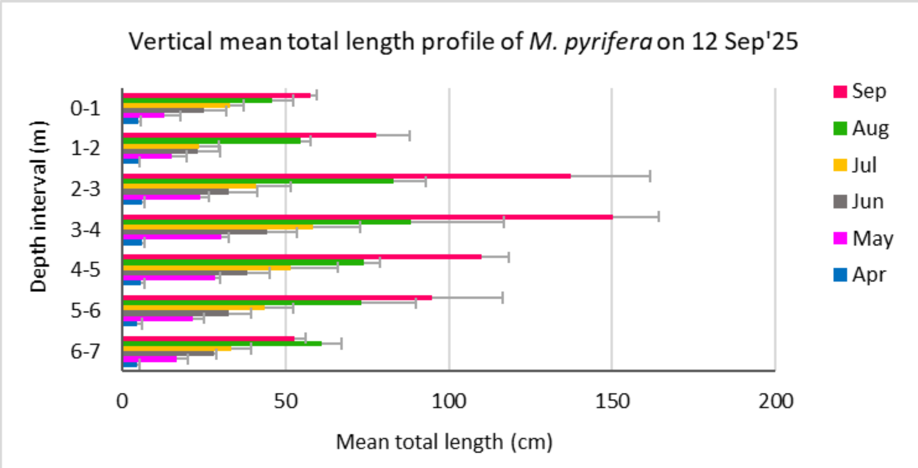


Figure 5 (b). Wet weight profile of the different components of the *L. pallida* dropper on 3 Oct'24 (Graph credit: Dr L Botes).

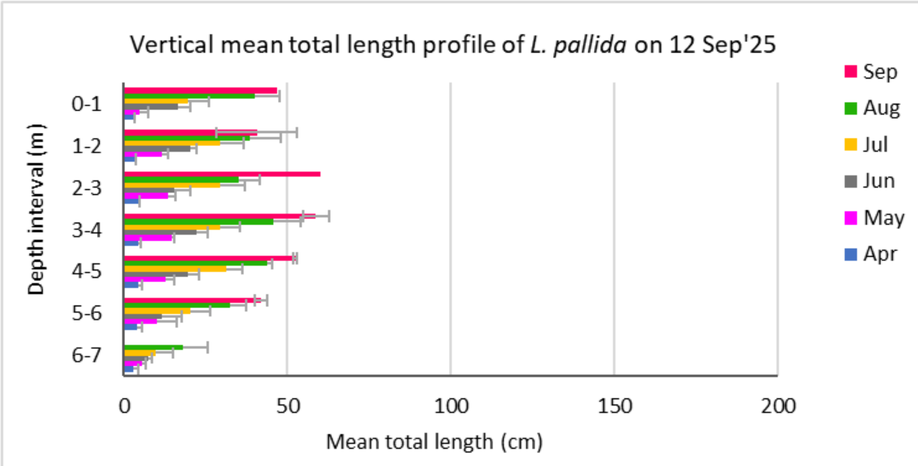
Given the lessons learned from these two grow-out seasons (summarised in Section 4 of this report), it was decided that the final and 3rd **grow-out season** from Mar'25 - Sep'25 would be dedicated to out-planting the spools with sporophytes from the POC based hatchery on 7 m rope droppers suspended from long-lines to verify data obtained to date. The progress thereof was monitored by the PA, Mr Musadiq Schalkwyk.

In confirmation of the 2024 data showing that *M. pyrifera* far outpaced *L. pallida* and *E. maxima*, Figure 6 shows the mean total lengths (cm) of kelps across three droppers in the case of *M. pyrifera* and *L. pallida* respectively, and across six droppers in the case of *E. maxima* until Jun'25. Due to two droppers being lost during winter, only four *Ecklonia* droppers were monitored from Jul - Aug'25. In Sep'25 only three droppers had remaining specimens. Ten randomly selected kelps at each depth interval of each dropper were measured to determine the mean total length (cm), however in the case of *L. pallida* and *E. maxima* this number decreased significantly as time went by. By 12 Sep'25 no *Ecklonia* specimens remained at the 1 - 2, 2 - 3, 5 - 6 and 6 - 7 m depth intervals (one specimen remained at the 3 - 4 m depth interval) and no *Laminaria* specimens remained at the 6 -7 m depth interval (one specimen remained at the 0 - 1 and 2 - 3 m depth intervals respectively).

(a)



(b)



(c)

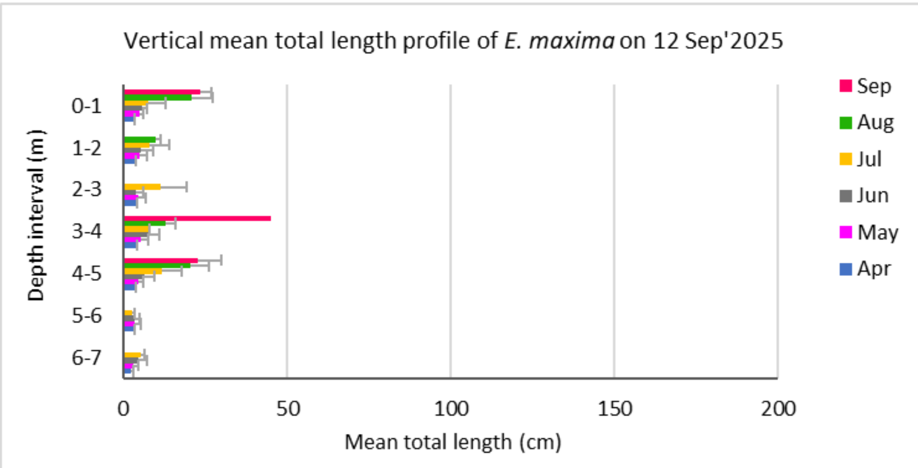


Figure 6. Comparison of the mean total lengths over **six months** in 2025 at each depth across droppers for (a) *M. pyrifera* (b), *L. pallida* and (c) *E. maxima*. Standard error bars indicate the spread/range of the data around the mean value. Where standard error bars are absent, only one kelp specimen was present. (Graph credits: Dr L Botes & Mr M Schalkwyk)

Figure 7 shows the mean total length comparison of the three kelp species over time, where the kelp length measurements of kelps present across the various droppers and across the various depths were averaged to obtain the mean total length per month per species.

(a)
(b)
(c)

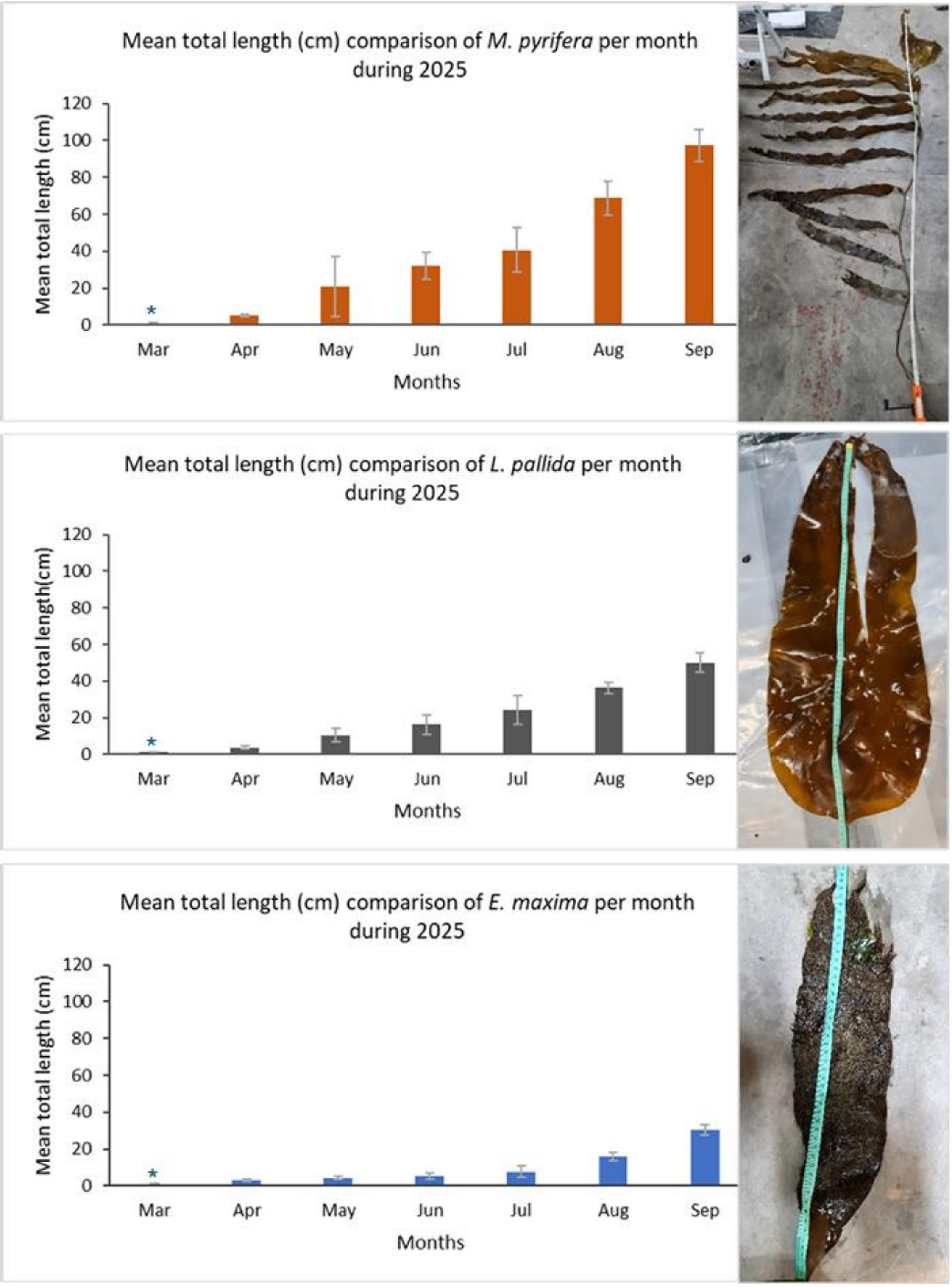


Figure 7. Mean total length of (a) *M. pyrifera* (b) *L. pallida* and *E. maxima* (c) during 2025. Standard error bars indicate the spread/range of the data around the mean value. (Graph credits: Dr L Botes & Mr M Schalkwyk, Photo credits: Dr L Botes)
* The mean total length of the kelps when the spools were out-planted in mid-Mar'25 was ~1 cm. The mean total length of the kelps after being in weaning for two weeks was ~2.5 cm by the end of Mar'25. Thereafter the kelps were measured once a month.

Although the kelps increased in length each month from Mar - Sep in 2025 (as seen in Figure 7), the greatest increase in length for all three species took place during the Jul - Aug and Aug - Sep time intervals as is seen in Figure 8. It should be noted though that, apart from losses such as storm damage, biofouling etc., the length measurements were also influenced by kelp lice grazing on blades, especially in the case of *E. maxima*.

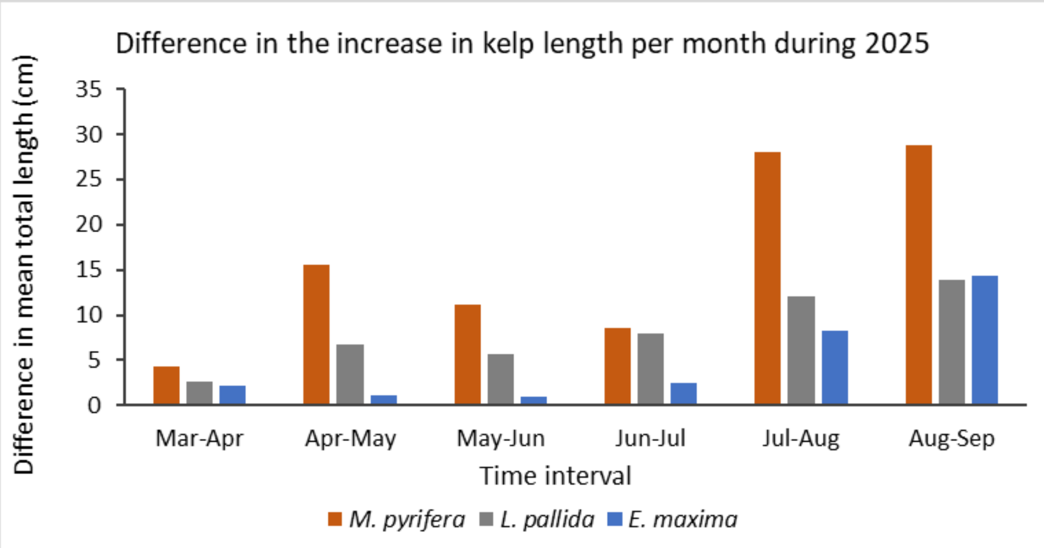


Figure 8. Difference in the increase in kelp length per month during 2025 (where the difference in mean total length = MTL2-MTL1). (Graph credit: Dr L Botes & Mr M Schalkwyk)

Moreover, the percentage of kelps surviving on the droppers from when initially out-planted in Mar'25 was higher for *M. pyrifera* in comparison to *L. pallida* and *E. maxima* (see Figure 9). This demonstrates that since *M. pyrifera* is well adapted to sheltered areas and the fact that it grows much faster and more able to rid itself from biofouling, the dropper rope structures and conditions at the BOM grow-out site in Small Bay are best suited for *M. pyrifera* and least suited for *E. maxima*.

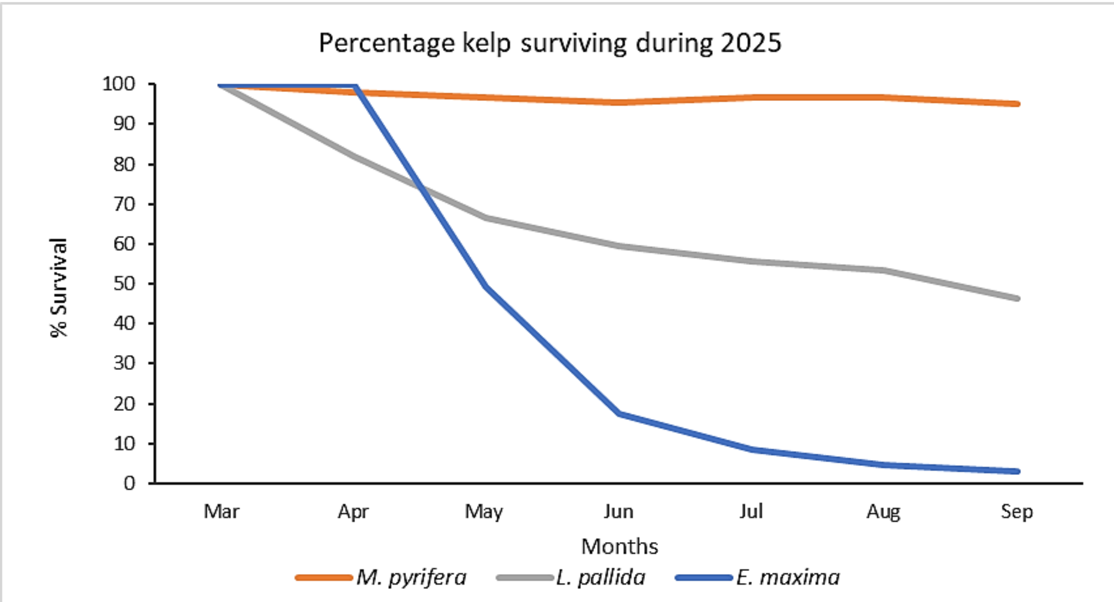


Figure 9. Percentage of kelps surviving from being out-planted in Mar'25 to Sep'25 when kelps were harvested. For *M. pyrifera* the total number of kelps counted across the various droppers and depths were n=210 in Mar'25 and n=200 by Sep'25, for *L. pallida* n=210 in Mar'25 and n=97 by Sep'25 while for *E. maxima* n=420 in Mar'25 and n=13 by Sep'25). (Graph credit: Dr L Botes & Mr M Schalkwyk)

Similar to the 2nd grow-out season in 2024, the 2025 kelp wet weights were calculated for the different components as indicated in Figure 10 a & b, with the total wet weight for the three *M. pyrifera* droppers 23.11 kg/dropper, 17.69 kg/dropper and 17.91 kg/dropper respectively while the total wet weight for the three *L. pallida* droppers was 10.05 kg/dropper, 3.12 kg/dropper and 3.46 kg/dropper respectively.

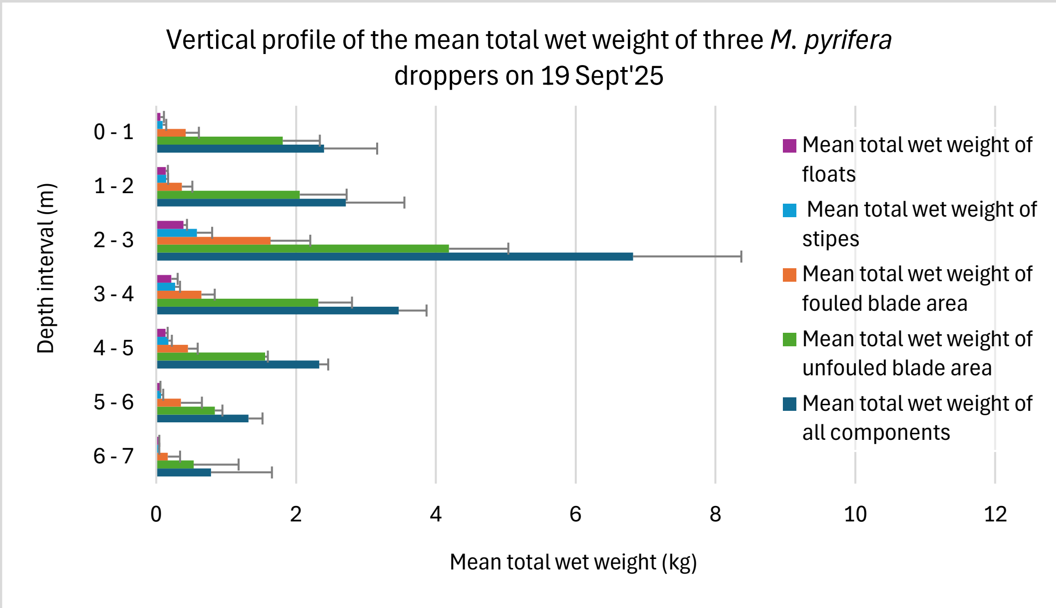


Figure 10 (a). Mean total wet weight profile of the different components of three *M. pyrifera* droppers on 19 Sep'25. Standard error bars indicate the spread of the data around the mean value. (Graph credit: Dr L Botes and Mr M Schalkwyk)

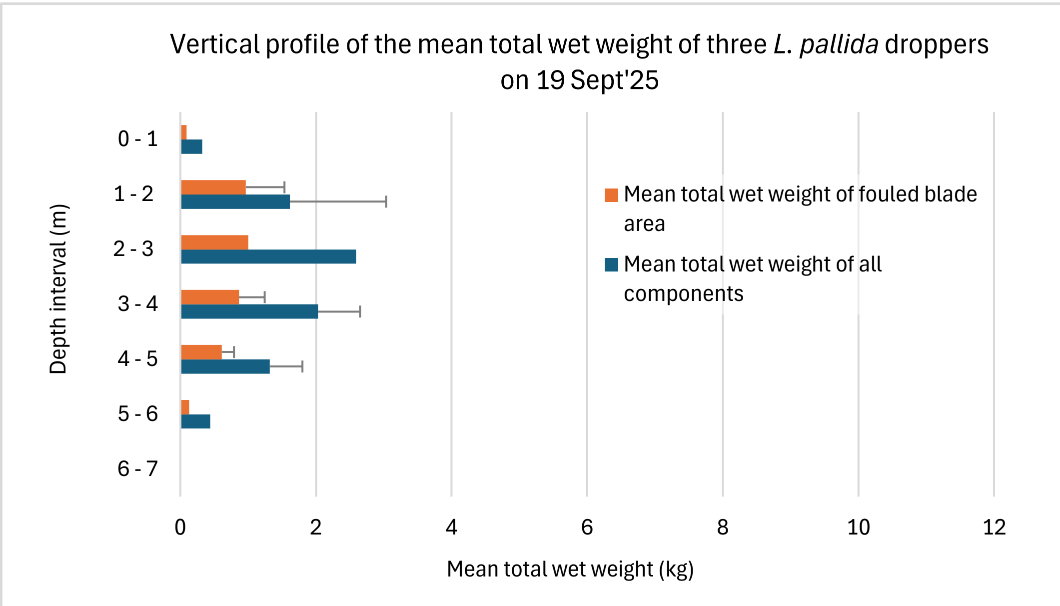


Figure 10 (b). Mean total wet weight profile of the different components of three *L pallida* droppers on 19 Sep'25. Standard error bars indicate the spread of the data around the mean value. Where standard error bars are absent, only one wet weight measurement was available. (Graph credit: Dr L Botes and Mr M Schalkwyk)

While the total wet weight of the fouled blade area for *M. pyrifera* was again less than 30% (as in the 2nd grow-out season), the total wet weight of the fouled blade area for *L. pallida* was more than 30% (i.e. 41.7%). The few remaining *E. maxima* specimens were almost entirely covered in biofouling (i.e. 81.9%). Additionally, the impact of the fouling on the quality of the blades was more severe than in the 2nd grow-out season, as is visible in Figures 11. Blades of *M. pyrifera* were mostly fouled with bryozoans and deformed by mussels, while the blades of *L. pallida* were mostly fouled with hydroids and deformed by bryozoans and the blades of *E. maxima* severely fouled with mussels, macroalgae and hydroids.

Figure 11. (a) *M. pyrifera* blades fouled with mussels, (b) *L. pallida* blade severly misshaped by bryozoans (c - e) *E. maxima* blades fouled with mussels, macro-algae and hydroids (Photo credits: Ms W Moosa).

2. Environmental influences determining the production cycle of kelps within Small Bay of Saldanha Bay

To effectively monitor environmental factors that would influence kelp growth and ultimately determine when the best time of the year would be to grow kelps in Small Bay, a comprehensive approach was taken by monitoring water quality, phytoplankton and biofouling. For this report, only the main findings will be presented. Since Saldanha Bay was altered by the construction of the man-made breakwater and the iron-ore jetty many during the 1970s, the findings are being discussed with specific reference to Small Bay as we suspect a similar study in Big Bay, Outer Bay as well as outside of Saldanha Bay, may yield somewhat different results.

At the BOM grow-out site, monitoring has revealed that the ideal time to out-plant the kelps is toward the end of March with the grow-out period between April - September (see yellow shaded area in Figure 11) when the water column is well-mixed with cool nutrient rich water below 15 °C. From October through to March each year, when the water column in Small Bay becomes stratified and the surface layers reach temperatures as high as 21.9 °C (range across depths 10 - 22 °C), the kelps significantly deteriorate in colour and physical appearance (see Figure 12, 13) as a result of the higher water temperatures in the upper layers of the water column, accompanied by extremely low nutrient concentrations (despite the occasional influx of upwelled water into Small Bay especially at depths from 6m and below), increasing phytoplankton concentrations (see Figure 15) and biofouling (see Figure 16, 17). The deterioration in the kelp blade colour was also observed in the wild kelp beds along the shoreline approximately 80 m from the grow-out ropes. Throughout the project, the pH remained within the 7.5 - 8.5 range whereas the DO concentrations had a small range in variation during winter but a wider range in variation during summer (results not shown here). A few extremely low DO events were observed during the upwelling season likely due to bacteria breaking down phytoplankton blooms and consuming oxygen in the process.

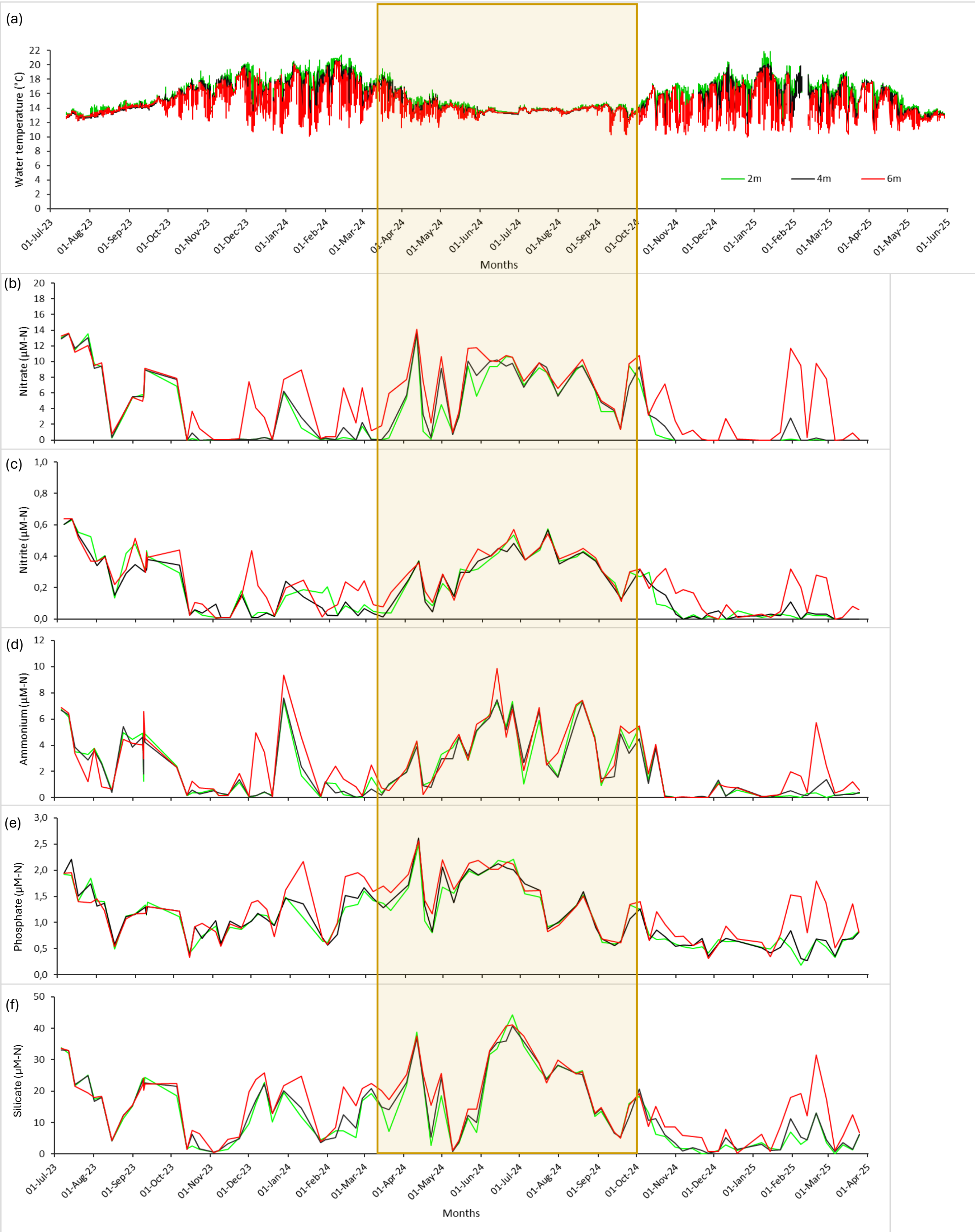


Figure 11. (a) Temporal variations in sea water temperature at 2 m, 4 m, and 6m in Small Bay from Jul'23 to Jun'25 (b - f) Temporal variation in nutrient concentrations at 2 m, 4 m, and 6 m in Small Bay from Jul'23 to Mar'25. **The shaded area shows the period best suited to grow kelps in Small Bay of Saldanha Bay.** (Graph credit: Dr L Botes, Sample/Data collection: Ms N Xulu and Mr M Schalkwyk)

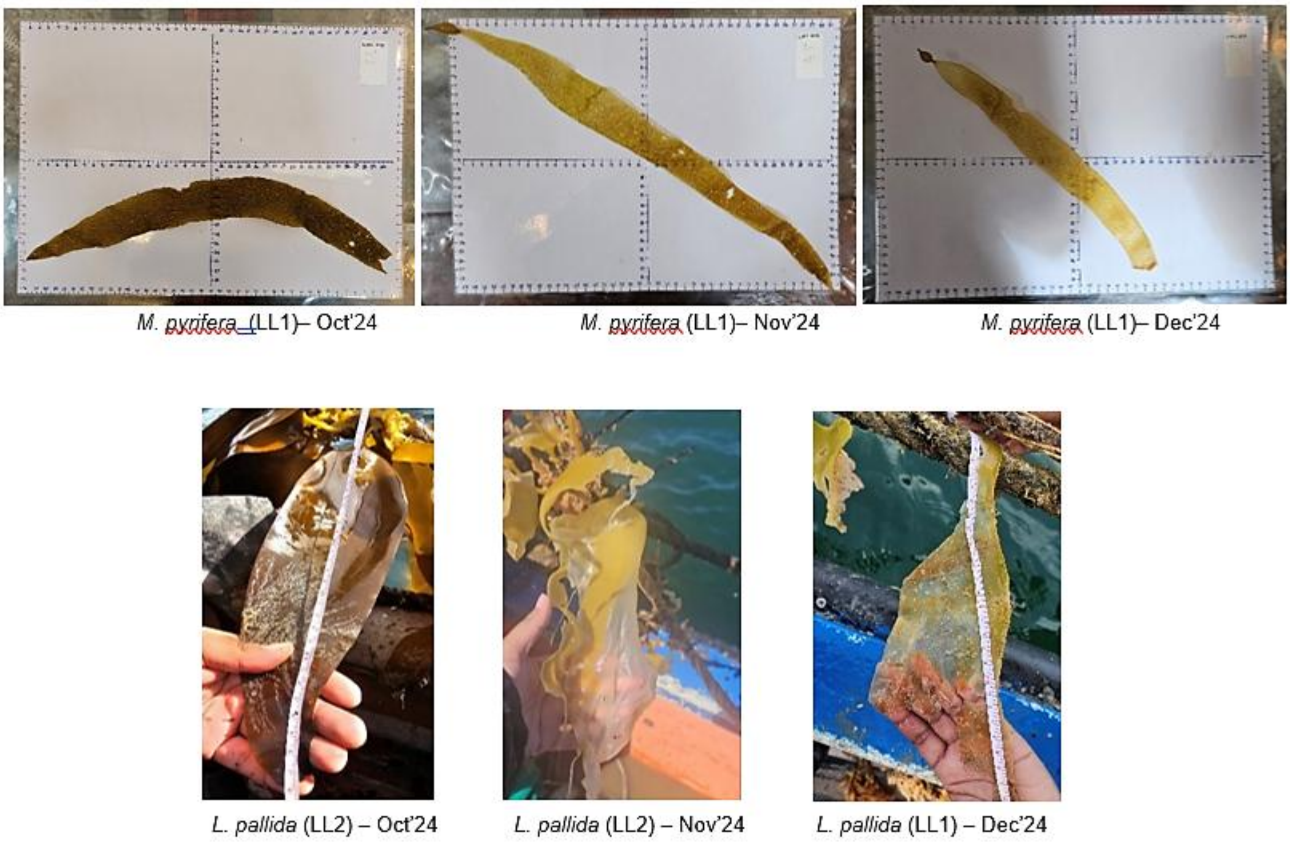


Figure 12. Loss of blade colour of *M. pyrifera* and *L. pallida* by the end of the year. (Photo credit: W Moosa)

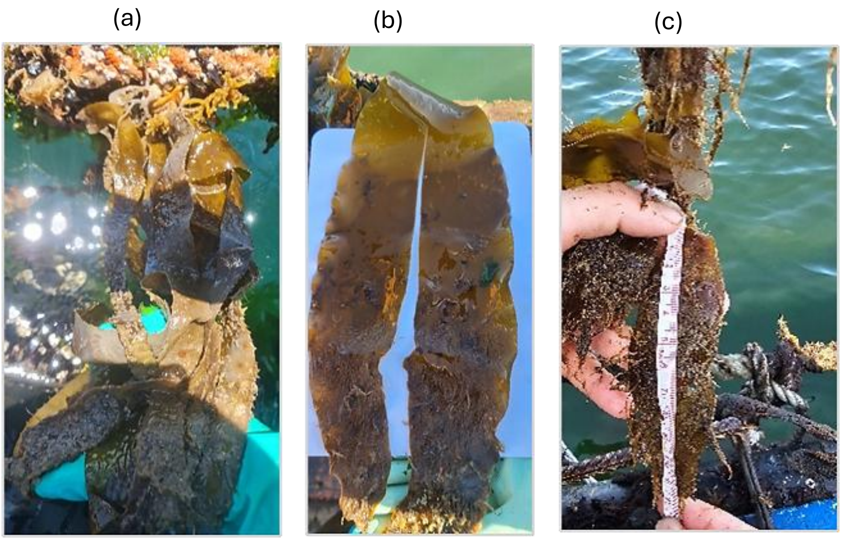


Figure 13. Blade deterioration of (a) *M. pyrifera* (b) *L. pallida* and (c) *E. maxima* by the end of the year due to biofouling (Photo credits: Ms N Xulu and Ms W Moosa).

Phytoplankton samples collected for the BSASA phytoplankton monitoring programme by Seawise Marine at 5 m depth (sampling site at BOM indicated in Figure 1) as well as the phytoplankton samples collected in this project at both long-lines containing the kelps, showed that the phytoplankton assemblage at BOM consisted mostly of diatoms with generally negligible concentrations of dinoflagellates (see the PM's 2024 - 2025 Q2 and Q3 - 4 reports for more details). While dinoflagellate concentrations are generally very low in comparison to diatoms, several harmful algae species (toxic and non-toxic) like the toxic dinoflagellate species *Alexandrium catenella,* *Gonyaulax polygramma* etc., do occur in the bay (and commonly on the west coast) which can affect not just the mussel and oyster farmers in the bay but also other marine organisms in particular the larval and juvenile stages.

This has relevance in several ways. Microalgae/phytoplankton (such as toxic and non-toxic dinoflagellates and diatoms) and macroalgae (like kelps and *Gracilaria*) compete for the same nutrients, can excrete allelochemicals to inhibit the other's potential for growth, can shade each other and prevent photosynthesis etc. While it has never been documented that kelps can or will absorb biotoxins from toxic microalgae (phytoplankton), it has been documented that toxin producing microalgae and bacteria can be present on the surfaces of kelp blades, therefore economic losses due to toxic dinoflagellate species such as *A. catenella*, *G. polygramma* and *A. sanguinea* will likely rather be due to bleaching of kelp blades as a result of decreasing nutrient concentrations in the water.

In our case, a bloom of *A. sanguinea* that peaked at the end of Jun'24/beginning Jul'24 dominated much of the west coast (including Saldanha Bay although to a lesser degree) stretching as far down as the south coast (Hermanus/Gansbaai area). Although this bloom did not reach cell concentrations inside the bay as high as the diatom blooms during the year, it is noteworthy that almost no other phytoplankton species were present at the time (with the exception of some *Ceratium* spp. - see the PM's 2024 - 2025 Q2 and Q3 - 4 reports for more details). During this time, we observed a distinct difference in the colour of the *Macrocystis* blades with blades looking much paler/yellower (see Figure 14 b) than the usual dark brown colour (see Figure 14 a), suggesting that the kelps were short of nutrients. However, a month later when the *A. sanguinea* bloom dissipated the blade colour was back to the normal deep brown colour (see Figure 14 c). On the flip side, we also observed that the blades had much less biofouling during the Jul'24 sampling than in comparison to Jun'24 samples. This may be due to some epiphytic species which grow on the *Macrocystis* blades becoming nutrient deficient and/or as a result of *A. sanguinea* killing many of the larval and juvenile stages of many of the epifaunal species living on the *Macrocystis* blades as it has been well documented in the literature that *A. sanguinea* affects a wide range of organisms especially the larval and juvenile stages.

Figure 14. *M. pyrifera* blade in (a) **Jun'24** showing dark colouration and biofouling (b) **Jul'24** showing lighter colouration and no biofouling (c) **Aug'24** showing dark colouration with biofouling starting to appear again (Photo credit: Ms W. Moosa).

During the sampling period from May - Dec'24 at BOM, there appears to be a very similar trend of the total average phytoplankton cell concentrations across the two long-lines (LL1 and LL2) even though cell concentrations are somewhat higher during May and June at LL2, which is closer to the mouth of the bay with water containing higher nutrient concentrations (see Figure 15 b). The latter part of the year is characteristic of a phytoplankton succession which follows colder months, when diatoms typically start blooming due to their ability to utilise silica-rich water available after winter mixing. This is usually followed by dinoflagellates which are mobile and able to migrate up and down the water column (to photosynthesise during the day in the top warmer layers and consume nutrients during the night in the colder bottom layers) through the thermocline when the water gets stratified during warmer months. Although cell concentration and species composition varied slightly, the spatial variation of the phytoplankton assemblage between 0 - 6 m across LL1 & LL2 was also very similar (for more information see Ms W Moosa's MSc thesis as listed in the table of Section 4.6 of the main report pp 22 - 23).

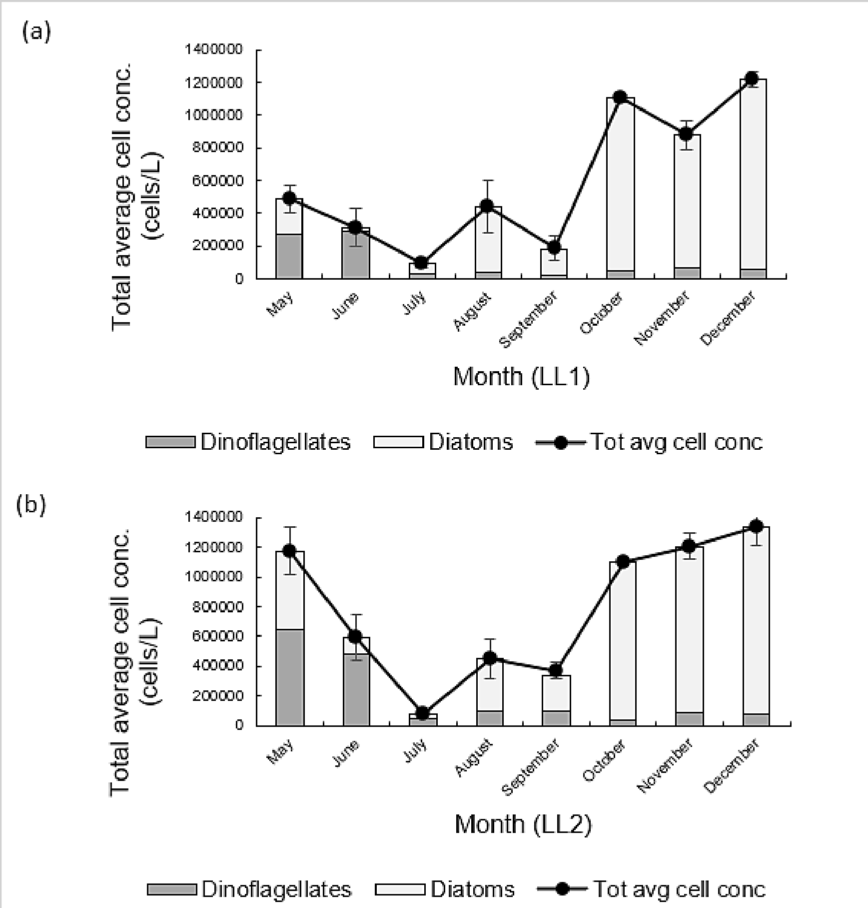


Figure 15. Total average phytoplankton cell concentrations at LL1 (a) and LL2 (b) during May-Dec'24. Standard error bars indicate the spread/range of the data around the mean value (Graph credit: Ms W Moosa)

It is worth noting that the higher average phytoplankton cell concentrations during Oct - Dec'24 (Figure 15) certainly contribute to the drop in nutrient levels (important to both phytoplankton and kelps) to near zero during these months (Figure 11 b - f). This increased phytoplankton biomass (responsible for primary production) sustains zooplankton (responsible for secondary production) which in turn sustains the entire marine food web in the months to follow, including the diversity of biofouling species. This also explains the presence of egg deposits of a variety of species found on the blades indicating that the breeding season of many of the biofouling species are aligned with the upwelling season. Moreover, it should be remembered that non-toxic microalgae are crucial to the filter-feeding oysters and mussels being grown in the bay.

Biofouling refers to the settlement of organisms on natural and artificial surfaces and include epibionts which either attaches to biological substrates like kelp blades for all or part of their life cycle. Kelps are known to support diverse communities of epiphytes (micro- and macroalgae growing on macroalgae) and epifauna (animals inhabiting the surface of other aquatic animals and macroalgae) on its blades, stipes and/or holdfasts that may in turn sustain higher trophic levels.

In the case of *Macrocystis* (Figure 16), the percentage of biofouling (% biofouling) on the kelp blades across the two long-lines were similar during the months of May to Aug'24 when the kelps were growing well and fast enough to rid themselves of most biofouling, while having access to sufficient nutrients in a well-mixed water column. However, from Sep'24 onwards the %biofouling on the blades were significantly higher at LL2 than at LL1 and for the most part more severe between 3 -6 m depths at both long-lines (more details available in Ms W Moosa's MSc thesis).

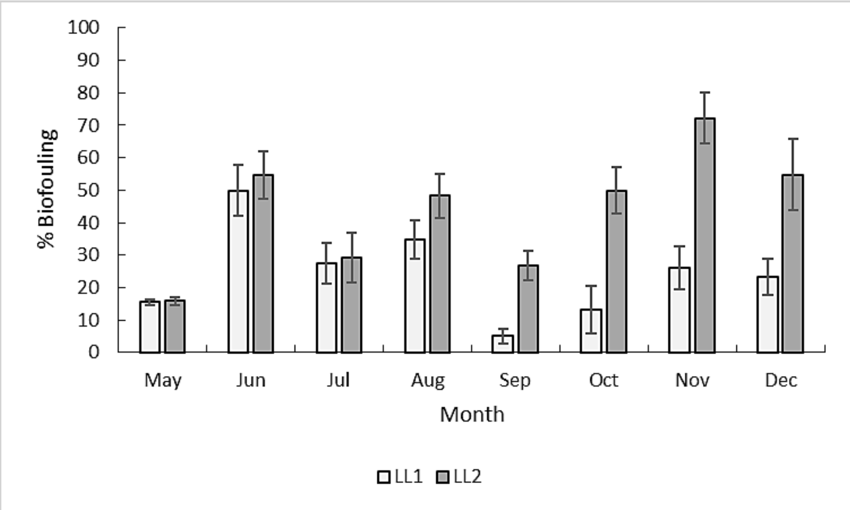


Figure 16 The % biofouling on *M. pyrifera* droppers at LL1 and LL2 from May-Dec 2024. Standard error bars indicate the spread/range of the data around the mean value (Graph credit: Ms W Moosa)

However, in the case of *Laminaria* (Figure 17), the %biofouling was mostly similar at both long-lines from Sep - Dec 2024 and for the most part more severe between 3 - 6 m depths at both long-lines (more details available in Ms W Moosa's MSc thesis).

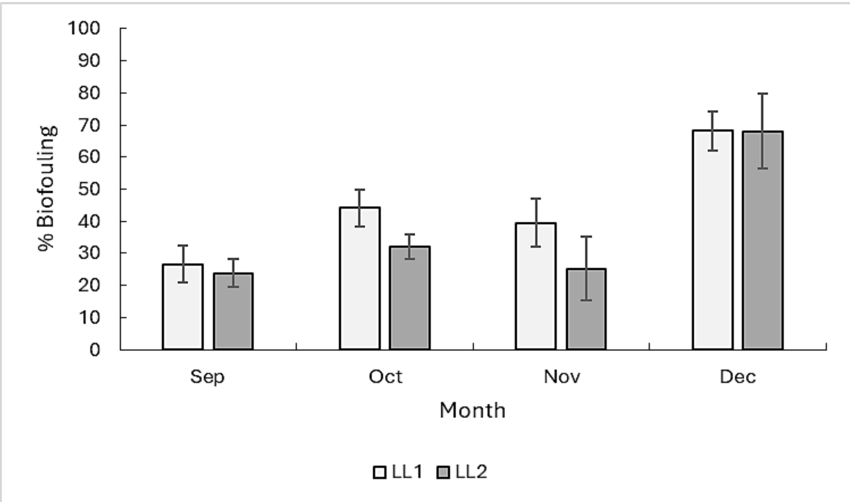


Figure 17. The % biofouling on *L. pallida* droppers at LL1 and LL2 from Sep-Dec 2024. Standard error bars indicate the spread/range of the data around the mean value (Graph credit: Ms W Moosa)

The species richness of epiphytes and epifauna on *Macrocystis* (total of 38 biofouling species) was much greater than on *Ecklonia* (total of 30 biofouling species) and *Laminaria* (total of 27 biofouling species). One of the reasons for this may be attributed to the morphological difference between the blades of *Macrocystis* (being corrugated and easier to settle on) as opposed to that of *Laminaria* and *Ecklonia* (being smooth and more difficult to settle on). However, despite the higher species richness of biofouling species on the blades of *Macrocystis*, it appears that *Macrocystis* is more capable of outcompeting these species either because it was in general healthier and grew faster (in comparison to *Laminaria* and *Ecklonia*), as it is better suited for the prevailing conditions in Small Bay, has better self-defence and/or self-cleansing mechanisms or a combination thereof.

Although both epiphytes and epifauna were present on the blades of all three kelps, the most common biofouling species on the blades of the kelps included skeleton shrimps, colonial bryozoans, hydroids, tube dwelling amphipods and mussel spat (see Figure 18) as well as red and green macroalgae species.

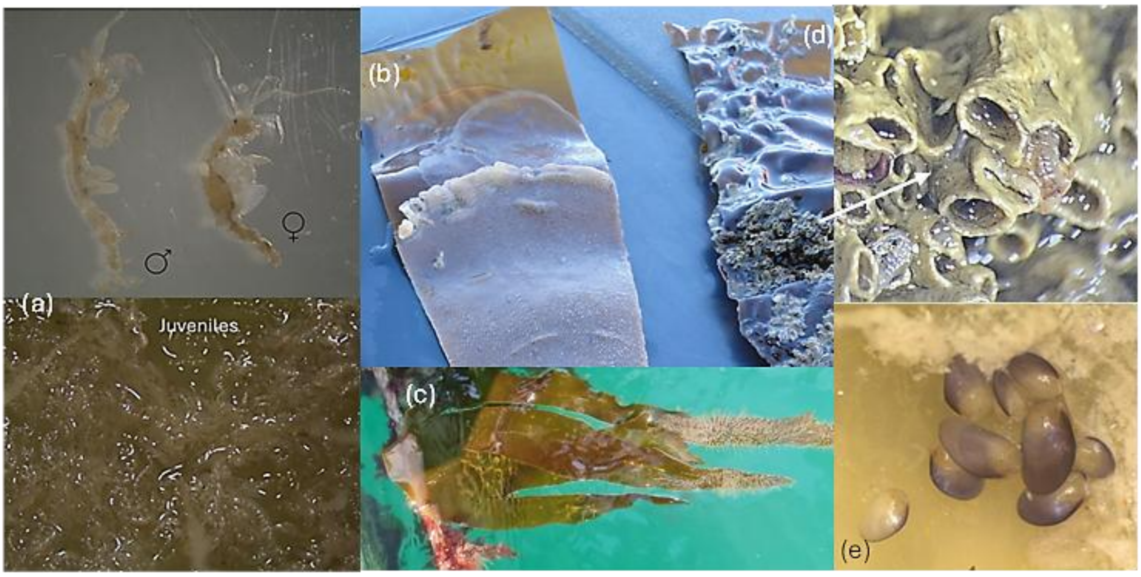


Figure 18. The most common biofouling species on kelp blades included (a) skeleton shrimps (b) colonial bryozoans (c) hydroids (d) tube dwelling amphipods and (e) mussel spat. (Photo credits: Ms W Moosa and Dr L Botes)

The most common biofouling on the main long-line and farm structures included tunicates on weights, encrusting barnacles and mussels on buoys and anchor lines, skeleton shrimps and mussels on ropes as well as various macroalgae on ropes (see Figure 19).

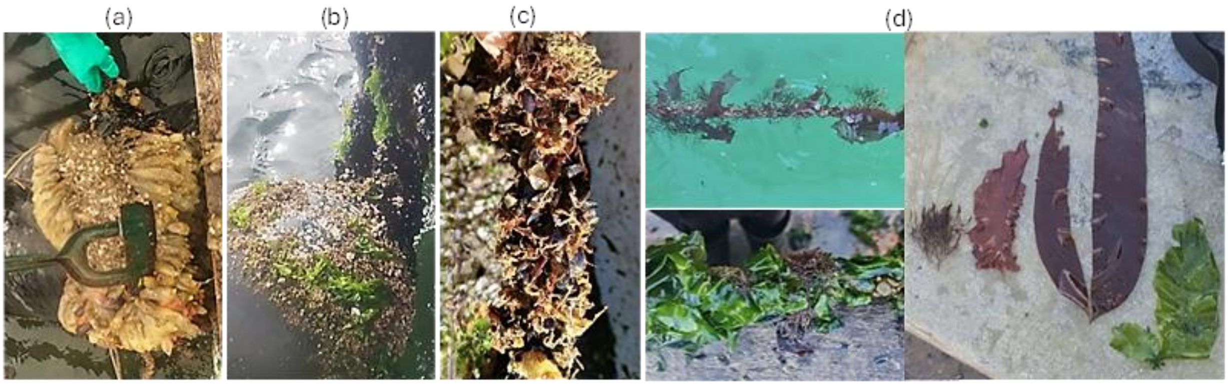


Figure 19. The most common biofouling on the main long-line and farm structures included (a) tunicates on weights, (b) encrusting barnacles and mussels on buoys and anchor lines (c) skeleton shrimps and mussels on ropes (d) various macroalgae on ropes (Photo credits: Dr L Botes and Ms N Xulu).

Arguably, the most problematic species are

(a) the kelp grazing isopod species *Paridotea* cf. *reticulata*, commonly known as the reticulate kelp louse (see Figure 20), which feeds on the kelps as well as the epiphytes on all three kelps. Early in the grow-out season, it seemed to initially specifically target the tips of the kelp blades likely due to the lower levels of polyphenols (acting as defence mechanism) in the tips of the blades as opposed to the higher levels in the meristem which enables blade growth, however later in the grow-out season when the majority of the *Ecklonia* blades deteriorated and became entirely fouled due to the unfavourable conditions for *Ecklonia* in Small Bay, the blades of *Ecklonia* became the easier target of the three kelp species.

Figure 20. *Paridotea* cf. *reticulata* commonly known as the reticulate kelp louse (Photo credit: Ms W Moosa)

(b) and the mussel spat from *Mytilus galloprovincialis*, (commonly known as the Mediterranean mussel) and *Choromytilus meridionalis* (commonly known as the South African black mussel) which are fierce competitors for space on the droppers of all three kelp species, as is seen on the *Ecklonia* rope (see Figure 21).

Figure 21. Mussels competing with *E. maxima* for space on grow-out ropes (Photo credit Dr L Botes).

Mussel fouling in Saldanha Bay will undoubtedly increase production costs (when separating and removing mussels when the kelps are being harvested), which will make it difficult to compete with wild harvested kelp prices where input costs are significantly lower.

3. <u>Kelp farming season</u>

If kelp farming were to take place in Saldanha Bay, the kelp farming season in Saldanha Bay will likely vary between Small Bay and Big Bay of Inner Bay as opposed to Outer Bay and open ocean farm sites.

Due to the change in the hydrodynamics of Saldanha Bay that has been altered by the construction of the man-made breakwater and iron ore jetty during the 1970s, leaving Small Bay much more protected than Big Bay and Outer Bay, it is unlikely that the kelp farming season as determined for

Small Bay (see Figure 22) will be identical for Big Bay and Outer Bay. While Big Bay experiences rougher conditions (and possibly more favourable for *L. pallida* and *E. maxima* farming), it will undoubtedly still be challenged by excessive mussel fouling (as in the case of Small Bay). Outer Bay and other more open ocean sites will face a much more challenging, high-energy wave environment. However, these latter sites will offer better access to nutrient-rich cold water from the Southern Benguela Upwelling System, potentially allowing for year-round kelp farming but such sites will no doubt require farming systems engineered for the powerful ocean wave energy along the South African coast.

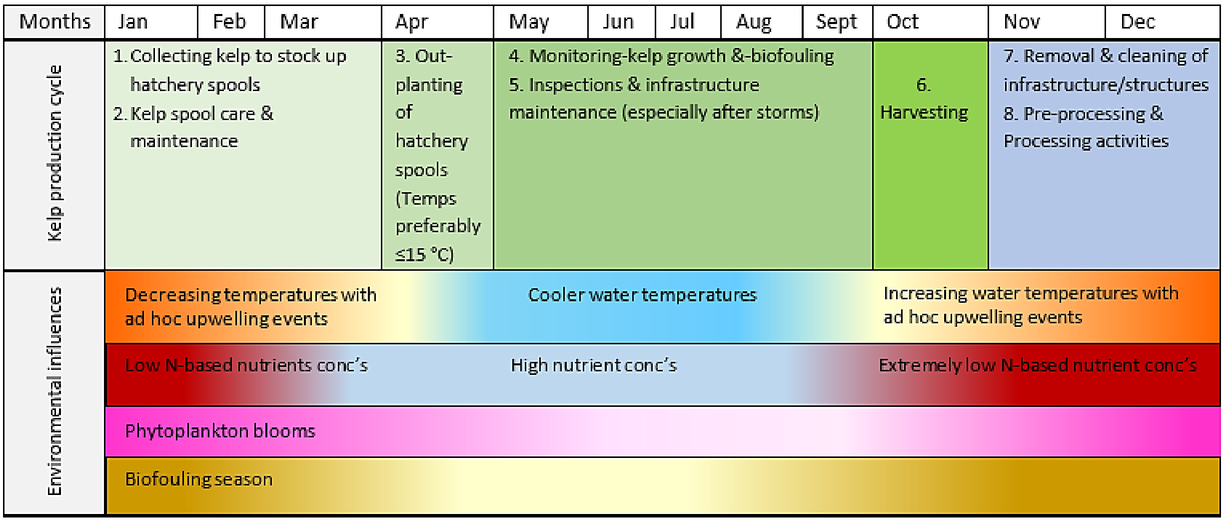


Figure 22. General kelp farming season timeline for kelp farming in Small Bay of Saldanha Bay (Diagram credit: Dr L Botes)

CONCLUSION AND RECOMMENDATIONS:

To fully understand how kelp farming can be done sustainably in SA, it will be best to do a similar study with the appropriate farming systems at a site with less mussel fouling pressure. Perhaps more importantly, even if kelp farming is possible, it is crucially important to establish if it can be done profitably and if indeed it will make business sense. The challenge for profitability will be to scale from an experimental small-scale manually focused operation (as was done in Phase 2 of this project) to a larger more automated commercially focused operation (as is done elsewhere in other parts of the world). While we have not yet had the opportunity to do a project at scale, this project has yielded several lessons that will lay the foundation and contribute to profitable kelp farming initiatives in SA.

ACKNOWLEDGMENTS:

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7.4 Nutritional value, Food Safety and Pre-preprocessing Report - compiled by BM Macey

SOUTH AFRICAN KELP FARMING PROJECT (SA KFP)

PROJECT REPORT ON THE NUTRITIONAL VALUE AND POTENTIAL FOOD SAFETY RISKS OF WILD AND FARMED AFRICAN KELPS IN SALDANHA BAY—AND APPROACHES FOR REDUCING HEAVY METAL, ARSENIC AND IODINE CONTENT

Report compiled by: Dr Brett M Macey (Department of Forestry, Fisheries and the Environment, South Africa).

Contributors: Dr Lizeth Botes, Prof John J. Bolton & Mr Musadiq Schalkwyk.

EXECUTIVE SUMMARY

The global seaweed aquaculture industry is growing rapidly and is being driven by an ever-increasing demand for seaweeds (especially kelps) for use as food, food supplements, nutraceuticals, functional foods, fertiliser and plant growth enhancers. Seaweed cultivation has also been shown to have positive ecosystem impacts—by extracting nutrients, providing shelter to marine species, and improving local biodiversity. However, the extractive abilities of seaweeds mean they can accumulate other elements, including certain trace elements and heavy metals and other toxic compounds should they be present in the environment. Since the accumulation of these compounds is dependent on seaweed type, physiology, season, and environment, it is essential to examine the nutritional and chemical composition of seaweeds at or near the site of cultivation to determine potential benefits and/or risks should these seaweeds be considered as feed for animals or food for humans. Moreover, should risks exist, methods should be developed to mitigate these risks. Therefore, the objectives of this study were to investigate the nutritional value and potential food safety risks—and approaches for reducing heavy metal, arsenic and iodine content—of wild and farmed southern African kelps (*Macrocystis pyrifera*, *Laminaria pallida*, and *Ecklonia maxima*) in Saldanha Bay in the Western Cape Province of South Africa (SA). Saldanha Bay is the only available large, sheltered embayment on the west coast of SA and, for this reason, is the site selected to assess the potential commercial viability of kelp inshore farming as part of the South African Kelp Farming Project (SA KFP).

Wild (*L. pallida* and *E. maxima*) and cultivated (*L. pallida* and *M. pyrifera*) kelps were collected during Sep/Oct of 2023 and 2024 in the Saldanha Bay Aquaculture Development Zone (ADZ) (33°02'05"S 18°00'35"E). Additionally, baseline nutritional data of wild harvested kelps was determined during Phase 1 of the SA KFP in 2022. The wild kelps collected from Saldanha Bay during Phase 2 of the SA KFP were consequently tested for potential food safety risks, including dioxin-like and non-dioxin-like PCBs, dioxins and furans; perfluoroalkyl substances, polycyclic aromatic hydrocarbons (PAHs), metals (cadmium, lead, mercury, mercury speciation, arsenic, inorganic arsenic), and pesticides. Conversely, the kelps cultivated in Saldanha Bay were subjected to both food safety and nutritional analysis as well as pre-processing tests—allowing for a comparison of food safety risks and the nutritional content of wild harvested and cultivated kelps, and determination of the effects of pre-processing (blanching) for lowering the heavy metal, arsenic and iodine content of the three southern African kelps.

Both wild harvested and cultivated kelps from Saldanha Bay exhibited a high nutritional content. The crude protein contents of cultivated *M. pyrifera* and *L. pallida* were within the range of crude protein contents (7-24 % DW) reported for several other brown seaweed species—suggesting that they're a good source of dietary protein for inclusion in animal and human food. The ash content—containing macro-minerals and trace elements—of both seaweeds was also high (26.08±1.66 % and 46.74±2.95 % for *M. pyrifera* and *L. pallida*, respectively). Among the minerals, the content of iron (Fe), zinc (Zn), aluminium (Al), arsenic (As), sodium (Na) and potassium (K) was consistently the highest, supporting findings of several other studies for a variety of seaweed species. The high mineral content suggests southern African kelps could have important health benefits—as minerals of seaweeds have been shown to contribute to several metabolic processes, serve as cofactors of many enzymes, and contribute to energy metabolism as well as cardiovascular health. Seaweed lipid contents were low, which is typical of seaweeds that often contain less than 1 gram lipid per 100 g dry weight. Kelps cultivated in Saldanha Bay were no exception, with a lipid content of 0.78±0.09 and 0.82±0.096 % recorded for the *Macrocystis* and *Laminaria*, respectively. Polyunsaturated fatty acids (PUFAs) were the most abundant of the FA's

followed by the saturated fatty acids (SFAs) and monounsaturated fatty acids (MUFAs). The most abundant SFA was 16:0 (Palmitic acid), which accounted for 20.6±4.7% and 17.1±3.9 % of the total FA methyl esters for *Macrocystis* and *Laminaria*, respectively. Of the MUFAs, 18:1n-9c (oleic acid) was most abundant in the kelps analysed from Saldanha Bay. Both kelps displayed a high content of the PUFAs 20:4n-6 (arachidonic acid; 16.1±3.6 & 16.9±3.8 % for *M. pyrifera* and *L. pallida*, respectively) and 20:5n-3 (eicosapentaenoic acid (EPA); 12.8±2.9 % in *M. pyrifera*), while the content of DHA (22:6n-3) was much lower (2.95±0.67 %). EPA is an Omega-3 fatty acid that plays an important role in anti-inflammatory, anti-thrombotic and anti-arrhythmic (cardiac arrythmia) responses—hence this FA species may provide numerous health benefits following consumption. The carbohydrate content of most seaweeds is high, typically 50-60 % of the dry weight of the seaweed, and kelp carbohydrates have several reported health benefits—including their contribution to weight loss, reduced cholesterol levels, and supporting a healthy gut microbiome. The carbohydrate content of the cultivated kelps in this study fell within this range (60.09 and 40.57 g.100 g^{-1} DW for *M. pyrifera* and *L. pallida*, respectively).

Although seaweeds typically have a high content of beneficial minerals, they can also accumulate non-desirable (toxic) heavy metals and trace elements (e.g., As) from their immediate environment. For both the wild harvested and farmed kelps collected from Saldanha Bay, the content of arsenic (As) > cadmium (Cd) > lead (Pb) > mercury (Hg). Total As was the highest in the cultivated *Macrocystis*, followed by the wild harvested *Ecklonia* and *Laminaria*, with the lowest As content detected in the cultivated *Laminaria*. Seaweeds are particularly abundant in As due to their propensity to absorb marine arsenic. Levels of total (non-toxic organic and toxic inorganic) As recorded in all Saldanha Bay kelps were above the maximum levels (MLs) allowed for seaweeds used as feed(s) however, the levels of inorganic As were substantially lower (< 0.2 mg.kg^{-1} DW) and well below the ML set by European Commission (EC) for seaweed used as feeds (2 mg.kg^{-1}) and French recommendations for edible seaweeds (3 mg. kg^{-1}DW). The heavy metal with the second highest content was Cd, with the highest values recorded for cultivated *Macrocystis* (1.36±0.28 mg.kg^{-1} DW), followed by wild harvested *Ecklonia* (0.73 – 0.95 mg.kg^{-1} DW) and wild *Laminaria* (0.59±0.12 mg.kg^{-1}). These values all exceeded the maximum level of 0.5 mg.kg^{-1} DW recommended by France for seaweeds that are used as feed and edible seaweed. Cadmium is a natural contaminant in the marine environment but can also enter aquatic systems from anthropogenic activities. Due to the Cd content of local kelps and many of the seaweeds examined to date exceeding regulatory limits, it is recommended that Cd be regarded as a contaminant that requires increased vigilance from a food safety/regulatory perspective. The levels of Pb reported in the present study were highest for the cultivated *Macrocystis* (0.88±0.20 mg.kg^{-1} DW) and appeared to be similar for the two wild harvested kelp species (*Laminaria* and *Ecklonia*), ranging from 0.21 to 0.29 mg.kg^{-1} DW. The lowest level of Pb was recorded for the cultivated *Laminaria* (0.12±0.027 mg.kg^{-1} DW). However, all the values recorded from South African kelps are well below the ML for feed (10 mg.kg^{-1}) and edible seaweed (5 mg.kg^{-1}) recommended by the EC and France. The levels of Hg in seaweed is typically low and was the heavy metal with the lowest concentration of all the non-essential metals in both the wild harvested and cultivated kelps collected from Saldanha Bay, with the recorded values (0.005–0.016 mg.kg^{-1} DW) well below the ML for feed (0.1 mg.kg^{-1}) and edible seaweed (0.1 mg.kg^{-1}) recommended by the EC and France. Iodine (I) is an essential trace mineral for both humans and animals and is found naturally in seaweeds. In France, the recommended ML of iodine is set at 2000 mg.kg^{-1} DW for all species of edible seaweed, particularly brown seaweeds. The iodide content of the *M. pyrifera* and *L. pallida* analysed from Saldanha Bay was 1240±230 and 5340 mg.kg^{-1} DW, respectively—similar to what has been reported for other brown seaweeds (1612–6568 mg.kg kg^{-1} DW).

Pesticide residues frequently enter the environment from agricultural practices and, due to limited information globally on the monitoring of pesticide residues, the EU has set a default maximum residue limit (MRL) of 0.01 $mg.kg^{-1}$ for most pesticides. Of the ca. 950 pesticides tested for in the current study, only two were detected in the South African kelps, Tribromoanisole and Tribromophenol. Tribromophenol occurred in all seaweeds (wild and cultivated) analysed from Saldanha Bay, whereas Tribromoanisole only occurred in the wild harvested *Ecklonia*. None of the other pesticides tested for were detected in this study. Several dioxin and dioxin-like PCBs were detected. Of the 19 PCBs monitored for in the kelps, 16 were detected in the cultivated *Macrocystis* and ranged in concentration from 0.007–8.4 $pg.g^{-1}$ DW, whereas 14 were detected in the cultivated *Laminaria* and ranged in concentration from 0.007–6.6 $pg.g^{-1}$ DW. However, more than 99% of the PCBs were below the cancer slope factor (CSF) limit from the USEPA Integrated Risk Information System database [8 $ug.kg^{-1}$ DW].

Seaweeds can accumulate a variety of harmful trace elements and heavy metals from their immediate environment, but among elements of concern, inorganic arsenic, cadmium, and iodine have been identified as major food safety hazards, while lead and mercury are regarded as moderate hazards. In the present study, the effects of two blanching methods—2-minutes of boiling or 20-minutes of steaming followed immediately by 5-minutes of rapid cooling in ice water—on the heavy metal (Cd, Pb and Hg), As and I content of *E. maxima*, *M. pyrifera* and *L. pallida* were investigated. We demonstrated that both boiling and steaming can significantly reduce the iodine content of all kelps, with the extent of the reduction being species dependent. Boiling was more effective for reducing iodine content, resulting in a reduction of 83.87 % ($P=0.004$), 58.92 % ($P<0.001$) and 70.37 % ($P<0.001$) for *Ecklonia*, *Laminaria* and *Macrocystis,* respectively. The effects of both pre-processing treatments were however not as pronounced for the other elements/metals, with no significant reduction observed in the content of As, Hg, Cd and Pb for either boiling or steaming for any of the kelps.

The high nutritional value observed in cultivated species like *Laminaria pallida* and *Macrocystis pyrifera* supports their use as valuable sources of proteins, minerals, and bioactive compounds for human and animal consumption. Implementing pre-processing methods, such as boiling or steaming, can effectively reduce the content of certain elements like iodine, improving food safety; however, the variable effects on heavy metals suggest that further optimization is needed. Continuous monitoring of chemical contaminants and heavy metals in farmed and wild seaweeds will be essential to mitigate potential health risks and ensure compliance with international safety standards. In this regard, there are on-going efforts by the DFFE and other research organizations (including the Cape University of Technology, University of Cape Town and the French IRD) to monitor the nutritional content and/or food safety risks of seaweeds of commercial importance in SA; and a committee has recently been established by the South African Bureau of Standards (SABS) and the DFFE to develop a draft seaweed standard. Overall, strategic research and development will optimize cultivation practices, processing techniques, and safety protocols, thereby enhancing the role of seaweed aquaculture in promoting health, environmental sustainability, and economic growth in SA and globally.

BACKGROUND

Seaweeds are a rich source of essential macronutrients, micronutrients, and bioactive molecules, including bio-available vitamins, minerals, pigments, proteins, bioactive peptides, dietary fibre, lipids, and phytochemicals—which play an important role in human (and animal) nutrition, health, and wellness (Hicks et al., 2019; Hua et al., 2019; Marques et al., 2021). Consequently, the seaweed aquaculture industry has grown, and continues to grow, rapidly worldwide and is being driven by an ever-increasing demand for seaweeds (especially kelps) for food, food supplements, nutraceuticals, functional foods, fertilizer and plant growth enhancers (Webb et al., 2023). Their cultivation has also been shown to have a positive impact on ecosystems, providing shelter to marine species, improving local biodiversity, and ecosystem services, such as the extraction of dissolved nutrients (Bizzaro et al., 2022). However, it has been shown that the nutritional content of seaweeds can vary substantially between species and is influenced by habitat, life-stage, maturity and environmental or culture conditions (Mengisteab et al., 2023). The extractive abilities of seaweeds also means that they can also accumulate other elements, including certain trace elements and heavy metals (e.g., As, Cd, Pb, Hg) and other toxic compounds (e.g., pesticide residues, dioxins, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and marine biotoxins), should they be present in the environment (Banach et al., 2019). Trace elements are the building blocks of matter and it is important to note that many of them are always present, naturally, in small amounts in the marine environment, but their extraction, production, use and release by human activities—including their emission and re-mobilization in the marine environment—can cause an increase of their environmental levels to concentrations that may become toxic to humans and animals (Richir and Gobert 2016; Tornero and Hanke 2016). Since the accumulation of these compounds is dependent on seaweed type, physiology, season, and environment, it becomes important to examine the nutritional and chemical composition of seaweeds at or near the site of cultivation to determine potential benefits and/or risks should these seaweeds be considered as feed for animals or food for humans.

Saldanha Bay is a key aquaculture zone in SA and presents a promising environment for further diversification and expansion of aquaculture activities in the Western Cape Province, owing to its proximity to major urban centres/ markets and favourable coastal conditions—including optimal temperature ranges, nutrient availability, clear water, strong currents and relatively sheltered waters (Kirsten & Tove, 2015). The existing aquaculture activities in the approved Aquaculture Development Zone (ADZ) in Saldanha Bay include mussels (*Mytilus galloprovincialis* and *Choromytilus meridionalis*) and Pacific oyster (*Crassostrea gigas*), which are well-suited to the local ecological and economic contexts (Meyer et al., 2018). Cultivation of bivalves, coupled with human activities (e.g., urbanization, sewage discharge), contribute to the nutrient load in the Bay and therefore make it a potentially suitable habitat for seaweed farming. Furthermore, government's support and increasing investment in sustainable aquaculture practices, including integrated multi-trophic aquaculture (IMTA) systems and the farming of low trophic species, enhance the prospects for further aquaculture development in the Bay (Van der Merwe & Joubert, 2020), particularly seaweeds, and the potential for Saldanha Bay to contribute meaningfully to SA's seafood industry and local livelihoods. However, the nutritional and chemical composition of seaweeds in the ADZ need to be determined to identify benefits and potential risks for their use as feed for animals or food for humans, and should risks exist, measures to mitigate against these risks need to be explored.

Various methods are routinely employed in the processing of seaweeds following collection from the wild or from cultivation sites. These include drying, boiling, steaming, or blanching—the latter entailing heating in boiling water or steam followed immediately by cooling in ice-cold water. Various combinations of the latter methods have also been used and depending on the intended downstream application, these processing techniques can significantly alter the final nutritional quality as well as food safety risks of the final product (Cascais et al., 2021; FAO, 2022). Seaweeds can accumulate a variety of harmful trace elements and heavy metals from their immediate environment (Guo et al., 2023), but among elements of concern, inorganic arsenic, cadmium, and iodine have been identified as major food safety hazards, while lead and mercury are regarded as moderate hazards (RASFF portal, 2021; RASFF portal, 2022; Anbazhagan et al., 2021; Banach et al., 2020). Processing methods, such as those listed above, can have a notable impact on reducing the content of these elements when present at harmful concentrations, but their efficacy can vary substantially between seaweeds and varies by element.

Therefore, the objective of this study was to investigate the nutritional value and potential food safety risks associated with wild and farmed southern African kelps (*Macrocystis pyrifera*, *Laminaria pallida*, and *Ecklonia maxima*) in Saldanha Bay in the Western Cape Province of SA—that are under consideration as nutritional and functional ingredients for human consumption and animal feeds—and to investigate approaches for reducing their heavy metal, arsenic and iodine content. The specific objectives of the present investigation were to determine the (1) nutritional value and potential food safety risks of *L. pallida* and *E. maxima* collected from natural populations in Saldanha Bay; (2) nutritional value and potential food safety risks of *L. pallida* and *M. pyrifera* cultivated in Saldanha Bay; and (3) effects of pre-processing (blanching) for lowering the heavy metal, arsenic and iodine content of these three southern African kelps.

METHODOLOGY

Collection of kelps and sample preparation

Wild kelps (*Laminaria pallida* and *Ecklonia maxima*) were collected in March 2023 in the Saldanha Bay Aquaculture Development Zone (ADZ) (33°02'05"S 18°00'35"E). This is the only available large, sheltered embayment on the west coast of SA (Lück-Vogel et al., 2024) and, for this reason, the site selected to assess the potential commercial viability of kelp inshore farming as part of the South African Kelp Farming Project (SA KFP). These kelps were tested for potential food safety risks, including dioxin-like and non-dioxin-like PCBs, dioxins and furans; perfluoroalkyl substances, polycyclic aromatic hydrocarbons (PAHs), metals (cadmium, lead, mercury, mercury speciation, arsenic, inorganic arsenic), and pesticides. Additionally, cultivated kelps (*L. pallida* and *M. pyrifera*, harvested in October 2024) were subjected to food safety, nutritional and pre-processing tests to allow for a comparison of food safety risks and the nutritional content of wild harvested and cultivated kelps—and to determine the effects of pre-processing (blanching) for lowering the heavy metal, arsenic and iodine content of these three local kelps.

Wild harvested kelps collected in this study included *E. maxima* and *L. pallida*. *Macrocystis pyrifera* was not collected as it does not occur naturally in Saldanha Bay, although populations are present on the nearby outer coastline (e.g., Jacobsbaai, Dassen Island). All samples consisted of blades only. One composite sample of blades from several plants of *L. pallida* (ca. 11 kg wet weight) was collected near Dial Rock in Small Bay in Saldanha, whereas two composite samples of *E. maxima* (ca. 10 kg each) were collected from within Big Bay in Saldanha—one sample in the vicinity of Club Mykonos and the other near the Die Strandloper Restaurant. The sample localities were chosen to provide an overview of possible hazards at the potential cultivation sites in the Bay and to determine whether difference would exist between the wild and cultivated species. The samples were placed in separate large Styrofoam boxes, labelled with species name/sample weight and immediately transported to Forever Fresh (https://foreverfresh.co.za/) in Somerset West (near Cape Town) for freeze-drying and packing prior to being submitted to the laboratories of Mérieux NutriSciences for food safety analysis (https://www.merieuxnutrisciences.com/za/).

The cultivated kelps *Laminaria pallida* and *Macrocystis pyrifera* sampled for nutritional and food safety analysis in this report were grown from hatchery spools on long-lines, deployed on ca. 6-meter droppers, at the Blue Ocean Mussel (BOM) cultivation site near the mouth of Small Bay in Saldanha Bay. Additionally, samples of this cultivated *M. pyrifera* were used to determine the effects of pre-processing—to determine the effects of two blanching methods (boiling & steaming) for lowering trace element and heavy metal content in this kelp. Due to a lack of sufficient quantities of cultured *Ecklonia maxima* and additional cultivated *L. pallida* material (at the time of this study) for the pre-processing trials, material for these two species were collected from the same two sites described above, where natural populations occur—Dial Rock in Small Bay for *L. pallida* and Club Mykonos in the outer bay (Big Bay) for *E. maxima*. Following collection, kelps were graded and sorted to ensure that only healthy blades, devoid of any visible epiphytes (e.g., bryozoans) were selected and processed for analysis (Figure 1). Healthy blades of *L. pallida* for nutritional and food safety assessment were placed in a large Styrofoam box, labelled with the species name and sample wet weight and immediately transported to Forever Fresh (https://foreverfresh.co.za/) in Somerset West (near Cape Town) for freeze-drying and packing prior to submitting the freeze-dried samples to the laboratories of Mérieux NutriSciences for nutritional and food safety analysis (https://www.merieuxnutrisciences.com/za/). Conversely, samples of the three kelps for pre-processing were packaged in separate, clearly marked, clean plastic bags and transported immediately to a nearby restaurant for pre-processing prior to analysis of selected trace elements and heavy metals (iodine, arsenic, mercury, cadmium and lead) (details provided below).

Pre-processing to determine the effects of two blanching methods (boiling & steaming) for lowering trace element and heavy metal content

Blades were cleaned thoroughly with tap water to remove excess salt, epibionts and other loose material, such as sand particles, before being cut into smaller (ca. 10 cm) strips prior to treatment for easier handling and more effective pre-processing. Three separate composite samples of ca. 700 g wet weight (WW) each were prepared for each kelp species per treatment—boiling, steaming and the control. Blanching is a cooking technique that involves briefly heating food in boiling water or steam, then immediately cooling it in ice water. We tested both variations in this study.

For boiling, the methods described by Good et al. (2021) and Stonington Kelp Co. (2019) were adopted, with minor modifications. Briefly, each composite sample was added to a pot of boiling seawater for 2-minutes. Following boiling, samples were immediately transferred to a container of ice-cold water for 5-min to stop the cooking process and help preserve the texture and nutritional quality of the kelps. Once cooled, the samples were placed in a colander to remove excess water before being placed in pre-labelled (with species, treatment replicate number and date) Zip-Lock bags and stored in a -20 ºC freezer. All equipment used for processing was thoroughly cleaned between each sample treatment and replaced with fresh sea-/tap- water prior to the next sample treatment to avoid any cross-contamination between samples.

For steaming, the methods described by Krook et al. (2023) and Yang et al. (2023) were adopted. Cut cleaned blades of each composite sample were placed in a Phillips HD-9140 steamer and steamed for 20-min before being rapidly cooled in ice-water for 5-min and packaged for freezing as described above for the boiling treatment. Control samples for each species were cut and cleaned, as described for the treatment samples, but were immediately packaged and placed in the -20 ºC freezer. All packaged and frozen samples were transported to Forever Fresh in Somerset West for freeze-drying, before being submitted to the laboratories of Mérieux NutriSciences for trace element and heavy metal (iodine, arsenic, mercury, cadmium and lead) analysis.

Figure 1. Collection of cultivated *Laminaria pallida* blades from long-lines at Blue Ocean Mussel farm in Saldanha Bay for nutritional and food safety analysis (a, b); grading and sorting of kelps to ensure that only healthy blades, devoid of any visible epiphytes, were selected and processed for analysis (c); pre-processing (blanching) of kelps (d); and preparation of kelp blades—packing and freezing of cut blades on stainless steel racks—for freeze-drying prior to nutritional and food safety analysis (Photo credits: Prof JJ Bolton, Dr L Botes and Mr M Schalkwyk).

Analytical methods

<u>Determination of minerals</u>

Minerals were analysed at the laboratories of Mérieux NutriSciences. The trace elements Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Sb, Hg, and Pb were analysed by means of inductively coupled plasma mass spectrometry (ICP-MS), after acid digestion. The elements Na, Mg, K, Ca and P were analysed by inductively coupled plasma optical emission spectroscopy (ICP-OES). All samples were subjected to acid digestion prior to ICP-OES analysis. Following digestion, nebulized samples were transported to the plasma torch and the element specific emission spectra were dispersed by a grating spectrophotometer. The intensities of the emission lines were monitored by the photosensitive device, and through the realization of calibration curves the quantity of each element was determined. Iodine was determined by means of ICP-MS. For determination of arsenic speciation, chromatography coupled with Inductively Coupled Plasma Mass Spectrometry (IC-ICP-MS) was used to determine trivalent arsenic (AsIII) and pentavalent arsenic (AsV)—the two most common forms of inorganic arsenic. The inorganic arsenic (iAs) was expressed as the sum of the two inorganic forms of arsenic AsIII and AsV.

Additionally, monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA) were determined. These are organic arsenic compounds that are formed via metabolism of inorganic arsenic by living organisms. Samples were subjected to acid hydrolysis prior to injection into the ion chromatograph, and separation of individual arsenic occurred with an ion exchange column and phase gradient. The concentrations of the individual arsenic species determined in each composite sample was reported as elemental arsenic. Trace analysis of the main forms of mercury—inorganic mercury (Hg++) and methylmercury (MeHg)—was also conducted by IC-ICP-MS. Homogenized and extracted samples were injected into the ion chromatograph capable of delivering the aqueous mobile phase through the analytical column isocratically, coupled with mass spectroscopy Plasma Induction used as a detector.

Proximate and fatty acid analysis

Proximate (protein, lipid, carbohydrate, moisture, and ash content) and fatty acid composition of all samples were analysed at the laboratories of Mérieux NutriSciences. The protein content was determined by nitrogen analyser according to the Dumas method. Briefly, an aliquot of each composite sample to be tested was weighed and put into the combustion pipe at a temperature of 920 °C in an oxygen atmosphere. All interfering compounds were removed from the resulting gas mixture, whilst the nitrogenous compounds of the sample were converted to molecular nitrogen and then quantitatively determined by a thermal conductivity detector. Nitrogen was transformed to protein by a conventional multiplying factor equal to 6.25. The moisture content of all samples was determined by titration with the Karl Fischer reagent in the presence of an appropriate solvent (when necessary) and detection of the end point of the titration by electrometric method—Karl Fischer method (Fisher, 1935). The ash content was determined by gravimetry. Briefly, an aliquot of each sample was weighted in a capsule, calcined and incinerated in a muffle at 550 °C. The temperature was maintained until the organic substance was completely burnt and until obtaining a grey/white ash. Following incineration, samples were placed in a desiccator and left to cool before weighing each sample. Results were expressed in g.100 g^{-1}, as weight difference of the sample. Total crude fat content and fatty acid composition was determined by gravimetry, hydrolysis method. An aliquot of each sample was heat-treated with a dilute hydrochloric acid solution, before allowing the mixtures to cool. Each sample was filtered and the resultant residues washed, dried and subjected to extraction in Soxhlet with petroleum ether. Following removal of the solvent, residues were dried and weighed and results expressed as g.100 g^{-1}dry matter. Carbohydrates were calculated by difference. All analyses were performed in triplicate.

Determination of fatty acids and fat

Fatty acids and fats in each of the seaweed composite samples was determined by gas chromatography with flame-ionization detection (GC/FID) by the laboratories of Mérieux NutriSciences. Aliquots of each sample were added with internal reference materials and subjected to transesterification with a solution of sodium methoxide. Resultant solutions were neutralized and extracted with hexane and the organic phase analysed in a gas chromatograph equipped with a flame ionisation detector (GC/FID). The result were expressed as: polyunsaturated fatty acids> c20, saturated fatty acids, monounsaturated fatty acids, cis monounsaturated fatty acids, trans monounsaturated fatty acids, polyunsaturated fatty acids, cis polyunsaturated fatty acids, trans polyunsaturated fatty acids, sum of omega 3, sum of omega6, sum of omega9, sum of omega11, omega 3/omega 6 ratio, ratio of polyunsaturated fatty acids/monounsaturated fatty acids and ratio of polyunsaturated fatty acids/saturated fatty acids.

Determination of dioxin and dioxin-like PCBs, polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF)

Chlorinated biphenyl (CB) congeners, polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) in the seaweeds samples were determined by high-resolution gas chromatography/high resolution mass spectrometry (HRGC/HRMS) at the laboratories of Mérieux NutriSciences. PCBs, PCDDs and PCDFs are not very volatile molecules, are water-insoluble—but extremely lipid-soluble—and accumulate in living tissues, mainly animal/plant fat exposed to polychlorinated biphenyls and/or dioxins. Due to this molecular nature, the fat fraction of each sample was extracted using the Soxhlet (food solids) system and the lipid fraction was subsequently removed by purification using a multilayer column in presence of H_2SO_4 acidified diatoms powder and the resulting elute manually purified through passage in a silica column followed by an alumina column. The resulting post-purification elute, which was brought to small volume, was resuspended using a syringe standard diluted solution before injection in a HRGC/HRMS system.

Determination of pesticides and polycyclic aromatic hydrocarbons

Complete pesticide screening was determined by GC/MS/MS at the laboratories of Mérieux NutriSciences. The principles were extracted from the matrix by means of a suitable solvent. The extracts obtained from each sample were then added with QuEChERS salts and analysed by gas chromatography equipped with a mass detector (triple quadrupole). On the other hand, polycyclic aromatic hydrocarbon (PAH) residues were determined by GC/MS at the laboratories of Mérieux NutriSciences. Each sample was subjected to saponification, followed by extraction of isopropyl alcohol using a suitable solvent through liquid-liquid partitioning. The resulting extracts from each sample were then purified using a solid-phase extraction (SPE) column, and the final solution was analysed using a gas chromatograph equipped with a mass spectrometer.

Statistical analysis

Results of the analysis from the pre-processing experiments are expressed as mean heavy metal content (mg kg^{-1} DW) (±SEM) of three replicate samples per treatment—boiling, steaming and the control. All data were checked for normality (Kolmogorov–Smirnov test) and homogeneity of variance (Bartlett's test). A one-way analysis of variance (ANOVA) was performed to analyse differences in metal content of specific kelp species within each treatment. All pairwise multiple comparisons were performed using the Holm-Sidak method/pot-hoc test when significant differences were found at $P < 0.05$. Statistical analyses were conducted using SigmaPlot 12.0.

RESULTS AND DISCUSSION

Proximate composition

The nutritional content of the *Macrocystis pyrifera* and *Laminaria pallida* cultivated in Saldanha Bay, expressed as grams per 100 g dry weight (DW), is shown in Table 1—together with other brown, red and green seaweeds analysed from Chile, for comparative purposes.

Marine algae are increasingly being recognised as a potential source of proteins, polysaccharides, dietary fibres, lipids, essential amino acids and vitamins. Seaweeds, particularly the red and brown seaweeds, are also a good source of source of n-3 and n-6 long-chain PUFAs, such as EPA and DHA as well as α-linolenic acid, linoleic acid, oleic and palmitic acids (Premarathna et al., 2022). Research has shown that the nutritional content of seaweeds can vary substantially with species, habitat, life-stage/maturity, and environment or culture conditions (Mengisteab et al., 2023). Of the two brown seaweeds analysed from Saldanha Bay, the crude protein content of the cultivated *M. pyrifera* (13.05%) was greater than that of the cultivated *L. pallida* (11.87%). However, the protein content of both seaweeds was similar to that of the brown (*M. pyrifera*) and red (*Gracilaria chilensis*) wild harvested seaweeds from Chile, but higher in protein content than the green seaweed (*C. fragile*) analysed in the Ortiz et al. (2009) study. These findings support previous research showing that the brown and red seaweeds generally have a higher protein content than green algae, grown in natural environments. Similarly, Campos et al. (2022) analysed the proximate composition, together with the profile of fatty acids and minerals, of four edible seaweeds cultivated in an integrated multitrophic aquaculture system in Portugal and found that the protein content was highest in the red alga *Porphyra* sp. (23.7 %) and ranged from 14.4 – 15.6 % in the three other species analysed (two Rhodophyta, *Chondrus crispus* and *Palmaria palmata*, and one Chlorophyta, *Ulva* sp.). Even though the protein contents of the *M. pyrifera* and *L. pallida* in our study were not as high as the *Porphyra* sp. in the latter study—which generally has high N levels in nature, but most likely also further elevated due to higher nutrient levels within the IMTA system—the values recorded in this study were within the range of protein contents (7–24 % DW) reported for several other kelp species (Forbes, 2009; Pacheco et al., 2021)—suggesting that these two kelps are a good source of dietary protein for inclusion both in animal (especially marine species) and in human food.

Table 1. Nutritional composition of *Macrocystis pyrifera* and *Laminaria pallida* cultivated in Saldanha Bay in SA versus *Codium fragile*, *Gracilaria chilensis* and *Macrocystis pyrifera* collected in the wild from Chile (Ortiz et al., 2009).

Species	Ash [% dry weight]	Protein	Lipid	Carbohydrate†	Calories
C. fragile [Wild harvested, Chile]	20.9±0.2	10.8±0.0	1.5±0.0	33.8±0.4	323.9
G. chilensis [Wild harvested, Chile]	18.9±0.1	13.7±0.2	1.3±0.0	66.1±1.2	330.9
M. pyrifera [Wild harvested, Chile]	10.8±0.3	13.2±0.0	0.7±0.1	75.3±0.2	360.3
M. pyrifera [Cultivated, RSA]	26.08±1.66	13.05±0.76	0.78±0.09	60.09	215.14
L. pallida [Cultivated, RSA]	46.74±2.95	11.87±0.74	0.82±0.096	40.57	149±16

†Obtained by difference: 100% – (%ash + %proteins + %lipid) and includes dietary fibre.

In comparison to most land plants, the ash content of seaweed—which contains all the macro-minerals and trace elements required for human nutrition—is high, typically ranging from 8-40 % of the dry weight (Rupérez, 2002; Muñoz and Días 2020). Seaweed ash content has also generally been shown to be higher in brown and red seaweeds than in the green seaweeds. For example, an evaluation of the proximate composition of green (*Ulva lactuca* and *Enteromorpha intestinalis*), brown (*Sargassum ilicifolium* and *Colpomenia sinuosa*) and red (*Hypnea valentiae* and *Gracilaria corticata*) seaweeds collected from the

Persian Gulf of Iran showed that *S. ilicifolium* had the highest ash content (29.9 %), whereas the lowest ash content was reported for *U. lactuca* (12.4 %) (Rohani-Ghadikolaei et al., 2011). Conversely, Campos et al. (2022) characterized the nutritional value of four edible seaweed species (*Chondrus crispus*, *Palmaria palmata*, *Porphyra* sp., and *Ulva* sp.) from Portugal and observed a similar ash content for the green *Ulva* sp. (25.5±0.09 %) and two of the red macroalgae in their study (*C. crispus* 26.0±0.31 % and *P. palmata* 25.7±0.12 %), with the *Porphyra* sp. exhibiting the lowest ash content (13.9±0.10 %). These findings once again highlight the importance of species type, habitat and/or environmental conditions in determining the nutritional content of a seaweed. Results from the present study support this, with the *M. pyrifera* and *L. pallida* harvested from the grow-out structures in Saldanha Bay exhibiting a high ash content (26.08±1.66 % and 46.74±2.95 %, respectively), which was higher than the ash content of species investigated from Chile by Ortiz et al. (2009). In fact, the South African *Macrocystis* was found to have more than double the ash content of the Chilean *M. pyrifera*. Depending on the composition of the macro-minerals and trace elements of the two South African kelps, they could have important health benefits as human and animal feed as the minerals of seaweeds have been shown to contribute to several metabolic processes, serve as cofactor of many enzymes, contribute to energy metabolism as well as cardiovascular health.

Lipids in seaweeds are typically low, less than 1 gram for 100 g dry weight, but their levels are similar to that of cereals (rice and rye) and legumes (common beans, chick-pea and broad bean), which is less than 2 %. The lipid content of the kelps cultivated in Saldanha Bay are no exception, with a lipid content of 0.78±0.09 and 0.82±0.09 percent recorded for the *Macrocystis* and *Laminaria*, respectively (Table 1). These values are within the range of lipid content values reported for a variety of other seaweed species, including the *M. pyrifera* analysed from Chilean waters by Ortiz et al. (2009) (Table1), several red, brown and green seaweeds—with lipid values ranging from 0.33±0.01 to 1.44±0.01 %—analysed by D'Armas et al. (2019) from Salinas Bay in Ecuador, as well as *Ulva* (as *Enteromorpha*) *intestinalis* (0.09±0.02–0.30±0.01 %), *Ulva lactuca* (0.28±0.03–1.06±0.12 %) and *Catenella repens* (0.14±0.02–0.25±0.02 %) specimens collected from six sampling stations over various months from the Bay of Bengal in India (Banerjee et al., 2009).

Conversely, the carbohydrate content of most seaweeds is high, typically comprising 50-60 % of the dry weight of the seaweed (Campos et al., 2022). This is a marked characteristic of seaweeds, with the carbohydrates mainly comprising soluble carbohydrates, sugars, and a large amount of alginic acid in the case of *M. pyrifera*. In the present study, the carbohydrate content of the cultivated *M. pyrifera* (60.09 g.100 g^{-1} DW) was higher than that of the *Laminaria* (40.57 g.100g^{-1} DW) (Table 1). The carbohydrate content of the *Macrocystis* in this study was lower than the carbohydrate content of the *Macrocystis* (75.3±0.09 %) analysed by Ortiz et al. (2009). As with the other parameters, carbohydrate content can vary significantly between species, and their synthesis is also favoured by environmental parameters such as light intensity, temperature and availability of nutrients (a decrease in nitrogen availability)—whereas for proteins these parameters are inversely related (Campos et al., 2022). Other factors, such as salinity (high salinity), have also been shown to favour carbohydrate content (Banerjee et al., 2021). The high carbohydrate content of seaweed is also what makes them an important source of phycocolloids (in kelp alginates) for industrial use. Overall, the carbohydrate contents of the kelps examined in this study are within the ranges reported for a variety of other seaweed species (Campos et al., 2022; Banerjee et al., 2021; D'Armas et al., 2019; Rohani-Ghadikolaei et al., 2011).

Mineral content and heavy metal content

The mineral contents of the cultivated *Laminaria pallida* and *Macrocystis pyrifera* collected from the Blue Ocean Mussel farm in Saldanha Bay in October 2024 and November 2023, respectively, are presented in Table 1. For comparative purposes, mineral contents of wild harvested *M. pyrifera*, *L. pallida* and *E. maxima* collected in December 2022, by Darias et al. (*unpublished data*) from Kommetjie—a small coastal town on the western side of the southern Cape Peninsula ca. 130 km South of Saldanha Bay—are also included (Table 2).

Seaweeds are well known for their rich mineral content, which can be as much as 10–20 times higher that of many terrestrial plants and their consumption has been shown to play an essential role in promoting health and the prevention of chronic nutrient-related as well as degenerative diseases—including cardiovascular disease, cancer and obesity (Muñoz and Días 2020; Premarathna et al., 2022).

These minerals are absorbed from the surrounding seawater, which makes seaweed rich in macro-elements and trace elements. The three-kelps analysed in this study are no exception, with a high mineral content observed in both the cultivated and the wild harvested kelps from the two sampling sites. Among the trace elements, the content of iron (Fe), Zinc (Zn), aluminium (Al), arsenic (As), sodium (Na) and potassium (K) was consistently the highest, supporting the findings of several other studies for a variety of seaweed species (Rupérez, 2002; Muñoz and Días 2020; Premarathna et al., 2022; Aknaf et al., 2024). Variation was also observed between the three analysed species and sampling locations. For example, the highest Fe content was observed in the cultivated *M. pyrifera* from Saldanha Bay, followed by wild harvested *E. maxima* from Kommetjie (Darias et al., *unpublished data*).

The levels of Fe in the cultivated *Macrocystis* were also substantially higher than the wild *Macrocystis* samples analysed from Kommetjie by Darias et al. (*unpublished data*). Both the content and composition of minerals in seaweeds is determined by the life-cycle stage/age of the seaweed, the surrounding environment, and the ability of the seaweed to absorb inorganic substances from the environment—which is facilitated by polysaccharides in their cell walls (Muñoz and Días 2020) as well as by other beneficial bioactive compounds within the seaweed that possess one or more metal binding sites (Yu et al., 2024). With regards to Fe, the Saldanha Bay Industrial Development Zone (IDZ)—where the BOM site is located—has an iron ore terminal and there is substantial iron ore dust pollution in the area, which most likely explains the high iron content (50 mg.100 g^{-1} DW) detected in the *Macrocystis* cultivated at this site when compared with wild *Macrocystis* collected from Kommetjie (3.99 mg.100g^{-1} DW) by Darias et al. (*unpublished data*). However, the *Laminaria* cultivated at the same site in Saldanha Bay had a much lower Fe content of 3.7 mg.100g^{-1} DW, a value similar to the other kelps analysed in this study from Saldanha Bay and in Kommetjie (range 3.3–8.4 mg 100 g^{-1} DW) by Darias et al. (*unpublished data*), and similar to *Laminaria* and other brown seaweeds (range 3.2–7.6 mg.100g^{-1} DW) analysed from Spain (Rupérez, 2002). This variation could be attributed to different uptake rates of this metal between *Macrocystis* and *Laminaria* but would have to be validated with additional sampling. Similar variations in the content of other minerals between species and sampling sites observed in this study (Table 2) and other studies does however support the notion that species and environment are important determinants of mineral content and composition in seaweeds.

Table 2. Mineral content of cultivated *Macrocystis pyrifera* and *Laminaria pallida* collected from Blue Ocean Mussel farm in Saldanha Bay during Phase 2 of the study, compared with the mineral contents of wild *Ecklonia maxima*, *Macrocystis pyrifera* and *Laminaria pallida* collected from Kommetjie near Cape Town by Darias et al. (*unpublished data*).

Sampling location	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Cd	Sb	Hg	Pb	Ca	K	Mg	Na	P
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
***Ecklonia maxima* [Wild]**	7360.11	558.22	1947.59	4669.92	83024.39	436.54	718.94	2558.91	18092.49	49546.00	25.00	1364.65	29.19	17.91	90.59	9521.18	66248.84	7773.64	40050.21	2396.20
***Laminaria pallida* [Wild]**	5931.03	495.11	517.43	3571.33	33462.98	450.50	661.03	1881.41	33155.00	58468.57	28.23	867.36	24.51	18.93	76.23	9371.03	69567.41	7570.40	37118.28	3602.79
***Macrocystis pyrifera* [Wild]**	67711.88	2443.15	606.03	4926.96	39915.37	193.73	678.86	1630.28	17830.82	85825.94	31.42	4369.43	32.57	18.43	117.15	9382.97	86756.35	7636.91	40929.27	4253.71
****Macrocystis pyrifera* [Cultivated]**	483000	2610.00	1670.00	9500	509000	115	1050	1370	24700	68000	388	1360	ND	10.1	880	24900	68000	7000	17200	3930
****Laminaria pallida* [Cultivated]**	8400	460	148	3540	37000	8.3 - 20	245	1540	18500	33900	ND	200	6.7 - 20	5.1	121	8100	3300	5700	34200	3300

*Samples collected and analysed by Darias et al. (*unpublished data*). **Samples collected and analysed in this study.

Because of the extractive abilities of seaweeds, they can accumulate not only desirable minerals but also non-desirable (toxic) heavy metals and trace elements (e.g., As) from their immediate environment. The heavy metal content of a seaweed is known to be influenced by the presence of these compounds in the environment and the uptake capacity of the species of seaweed concerned. For both the wild harvested and farmed kelps collected from Saldanha Bay (Table 3), the content of arsenic (As) > cadmium (Cd) > lead (Pb) > mercury (Hg) (Table 3). Among the elements, the content of total As was the highest in the cultivated *M. pyrifera*, followed by the wild harvested *E. maxima* and *L. pallida*, with the lowest content detected in the cultivated *Laminaria*. However, it is not possible to say whether these differences are significant due to the lack of replicates in this study (as only one composite sample was analysed per site). Marine aquatic organisms are a well-known major food source of non-toxic organic As (Muñoz and Días 2020), and kelps are particularly abundant in As due to their propensity to absorb marine arsenic—taken up by phosphorus pathways and converted to a variety of As-containing chemical species (Yu et al., 2024).

The major As compounds in seaweeds are organic arsenosugars and the levels of inorganic As are generally much lower—and often not reported on in many harvested seaweeds. The levels of total As in the kelps collected from Saldanha Bay are similar to the levels of As reported for the kelps collected from Kommetjie near Cape Town (49–59 $mg.kg^{-1}$ DW) by Darias et al. (in preparation) and also fall within the range of values reported for other kelps, such as *Saccharina* (52–91 $mg.kg^{-1}$ DW, Rolenda et al., 2019). Arsenic either occurs naturally in an environment (e.g., from soil, rocks, and natural waters) or enters from anthropogenic sources (e.g., fertilizers, pesticides, industrial activities) and occurs as either an organic or inorganic form (Banach et al., 2019). Inorganic As is more toxic and generally makes up a small proportion of the total As in tissues of most seaweeds. Although the levels of total As recorded in all South African kelps analysed in this study were above the maximum levels (MLs) allowed for seaweeds used as feed(s), according to European Commission regulations (Directive 2002/32/EC), the levels of inorganic As were substantially lower (< 0.2 $mg.kg^{-1}$ DW) and well below the ML set by European Commission for seaweed used as feeds (2 $mg.kg^{-1}$) and French recommendations for edible seaweeds (3 $mg.kg^{-1}$ DW) (EFSA, 2009) (EFSA, 2009).

The heavy metal with the second highest content in the tested seaweeds was Cd, with the highest values recorded for cultivated *M. pyrifera* (1.36±0.28 $mg.kg^{-1}$ DW), followed by wild harvested *E. maxima* (0.73–0.95 $mg.kg^{-1}$ DW) and wild *L. pallida* (0,59±0,12 $mg.kg^{-1}$DW) (Table 3). These values all exceeded the maximum level of 0.5 $mg.kg^{-1}$ DW recommended by France for seaweeds that are used as feed and edible seaweed. The only exception was the samples collected from the cultivated *L. pallida*, which had the lowest cadmium content of 0.2 $mg.kg^{-1}$ DW that did not exceed the maximum regulatory limit (0.5 $mg.kg^{-1}$ DW) for this metal. It is however worth mentioning that the values of Cd recorded in this study are within the range of Cd levels reported for other brown seaweeds (Banach et al., 2019; Hwang et al., 2010). Cadmium is naturally available in the marine environment but can also enter aquatic systems from anthropogenic activities—for example, from the manufacturing of materials such as paint, PVC products, batteries, fossil fuels, and fertilizers (Banach et al. 2019; Shaughnessy et al., 2023). Numerous studies have reported Cd in seaweeds and have shown that the levels of Cd can vary substantially among seaweed species, with the Rhodophyta (red seaweeds), such as *Porphyra* spp., and the Phaeophyceae (brown seaweeds), including the kelps *Undaria pinnatifida* and *Macrocystis pyrifera*, containing relatively high concentrations of Cd compared with most green algae species (Guo et al., 2023).

Table 3. Trace element and heavy metal composition of wild harvested *Laminaria pallida* and *Ecklonia maxima* collected from three sites in Saldanha Bay as well as the trace element and heavy metal content of *M. pyrifera* and *L. pallida* cultivated in Saldanha Bay, Western Cape Province, South Africa, compared to recommended maxima.

Hazard	**Seaweed and Location in Saldanha Bay**					**Maximum Levels**	
	Laminaria pallida, Dial Rock [Wild]	*Ecklonia maxima*, Club Mykonos [Wild]	*Ecklonia maxima*, Die Strandloper [Wild]	*Macrocystis pyrifera*, BOM & VIKING [Cultivated]	*Laminaria pallida*, BOM [Cultivated]	[a]Feed	[b]Edible Seaweed
Arsenic (Total)	58±12 mg.kg^{-1}	47.1±9,9 mg.kg^{-1}	61±13 mg.kg^{-1}	68±14 mg.kg^{-1}	33.9±7.1 mg.kg^{-1}	40 mg.kg^{-1}	-
Arsenic trivalent	n.d.	n.d.	n.d.	0.073±0.026 mg.kg^{-1}	n.d.	-	-
Arsenic pentavalent	0.0150±0,0077 mg.kg^{-1}	Traces	n.d.	0.121±0.042 mg.kg^{-1}	n.d.	-	-
Inorganic arsenic	0.0150±0.0077 mg.kg^{-1}	< LoQ	< LoQ	0.194±0.049 mg.kg^{-1}	<0.010 mg.kg^{-1}	2 mg.kg^{-1}	[c]3 mg.kg^{-1}
Dimethylarsinic acid	n.d.	n.d.	n.d.	0.53±0.18 mg.kg^{-1}	n.d.	-	-
Monomethylarsonic acid	0.030±0.012 mg.kg^{-1}	traces	0.0158±0.0079 mg.kg^{-1}	0.089±0.031 mg.kg^{-1}	n.d.	-	-
Mercury (Total)	0.0168±0.0050 mg.kg^{-1}	0.0154±0,0048 mg.kg^{-1}	0.0086±0.0037 mg.kg^{-1}	0.0101±0.0039 mg.kg^{-1}	0.0051±0.0034 mg.kg^{-1}	0.1 mg.kg^{-1}	[c]0.1 mg.kg^{-1}
Inorganic mercury	0.0163±0.0042 mg.kg^{-1}	0.0110±0.0037 mg.kg^{-1}	0.0118±0.0038 mg.kg^{-1}	0.0105±0.0036 mg.kg^{-1}	0.0015-0.005 mg.kg^{-1}	-	-
Monomethylmercury	n.d.	n.d.	n.d.	n.d.	n.d.	-	-
Cadmium (Total)	0.59±0.12 mg.kg^{-1}	0.79±0.16 mg.kg^{-1}	0.73±0.15 mg.kg^{-1}	1.36±0.28 mg.kg^{-1}	0.20±0.042 mg.kg^{-1}	0.5 mg.kg^{-1}	[c]0.5 mg.kg^{-1}
Lead	0.242±0.054 mg.kg^{-1}	0.289±0.065 mg.kg^{-1}	0.210±0.047 mg.kg^{-1}	0.88±0.20 mg.kg^{-1}	0.12±0.027 mg.kg^{-1}	10 mg.kg^{-1}	[c]5 mg.kg^{-1}

*All values above are based on a dry weight basis

[a]Directive 2002/32/EC specifies undesirable substances in animal feed. The level is relative to a feed with a moisture content of 12%.

[b]Regulation (EC) 1881/2006 on setting maximum levels for certain contaminants in foodstuffs. "The maximum level applies to the food supplements as sold."

[c]Based on French recommendations, the ML of Hg in edible seaweeds is 0.1 mg/kg DW (ANSES, 2018; CEVA, 2014).

A review of three genera and eleven species of the main edible seaweeds used for human consumption around the world by Muñoz and Días (2020) revealed that only the Chlorophyta contained Cd at concentrations within permissible limits, whereas the examined Rhodophyta and the Phaeophyceae exceeded the maximum acceptable limits for Cd. In the latter study, the Cd level of the *Laminaria* (0.4 $mg.kg^{-1}$ DW) was similar to the value recorded for *L. pallida* in our study, whereas the *M. pyrifera* samples examined by Muñoz and Días (2020) exhibited the highest Cd concentration (6.5 $mg.kg^{-1}$ DW) out of the brown algae they examined, supporting the findings of the present study and that of Banach et al. (2019)—who following examination of 52 green, red and brown seaweeds reported elevated average Cd concentrations in the Rhodophyta and Phaeophyceae—of which *U. pinnatifida* (the edible kelp wakame) had the broadest concentration range (0.267 to 4.82 $mg.kg^{-1}$ DW). Cadmium has a high half-life—meaning it can persist in tissues for extended periods—and cadmium's divalent nature allows it to form many stable complexes with biomolecules, altering their functionality (Paz et al., 2019). A well-known toxicological effect of Cd is its effect on the renal system of kidneys, causing irreversible damage to renal tubules and adversely affecting nutrient reabsorption (Paz et al., 2019; Guo et al., 2023). Since Cd content for many of the seaweeds examined to date in numerous published studies exceed regulatory limits, it is recommended that Cd be regarded as a contaminant that requires increased vigilance from a food safety/regulatory perspective (Hwang et al., 2010).

Lead (Pb) is a neurotoxic heavy metal that is frequently found in the environment, mostly because of its use in paints and fuel (Banach et al., 2019). Lead is a non-essential element for the human body and tends to accumulate in tissues, with excessive intake leading to significant damage of the central nervous system (CNS), particularly in developing children and foetuses, skeletal, circulatory, enzymatic, endocrine, and immune systems (Muñoz and Días, 2020). It can also cause kidney disease, gastrointestinal tract alterations, and is linked to Alzheimer's disease (Paz et al., 2019). Its chemical properties facilitate binding to phosphate groups of DNA/RNA, affecting gene expression in cells, and Pb is also responsible for the inhibition of more than 200 biologically important functions in the human body (Muñoz and Días, 2020). In the European Union, the ML for Pb in food supplements is 3 $mg.kg^{-1}$ DW (EC, 2023), but no regulatory limit exists as yet for seaweed and seaweed-based products (Guo et al., 2023). In France, the ML for Pb in edible seaweed is 5 $mg.kg^{-1}$ DW (CEVA, & Centre d.Etude et de Valorisation des Algues, 2014; ANSES, 2020).

The levels of Pb reported in the present study were highest for the cultivated *M. pyrifera* (0.88±0.20 $mg.kg^{-1}$ DW) and appeared to be similar for the two wild harvested kelp species (*Laminaria* and *Ecklonia*) from Saldanha Bay, ranging from 0.21 to 0.29 $mg.kg^{-1}$ DW. The lowest level of Pb was recorded for the cultivated *L. pallida* (0.12±0.027 $mg.kg^{-1}$ DW) (Table 3). All the values recorded from South African kelps are well below the ML for feed (10 $mg.kg^{-1}$) and edible seaweed (5 $mg.kg^{-1}$) recommended by the European Commission and France, respectively (Table 3). Values reported in this study are also within the range reported for other green, red, and brown seaweed species (Banach et al., 2019; FAO and WHO, 2012). Hwang et al. (2010) examined Pb concentrations is 26 samples of seaweed sold in Korea between the period 2007 – 2008 and found that the average Pb concentration in the examined seaweeds was 0.7 $mg.kg^{-1}$ DW and ranged from below the limit of detection (<LOD) to 2.7 $mg.kg^{-1}$ DW. Similarly, Almela et al. (2006) determined Pb concentrations in foods containing seaweeds sold in Spain and found that Pb concentrations ranged from <0.05–0.44 $mg.kg^{-1}$ DW (Banach et al., 2019). In both of the latter studies, as observed in the present study, the observed concentrations of Pb did not exceed the ML for food supplements or feed. Hwang et al. (2010) also observed no statistical difference in Pb concentrations between seaweed types, unlike what has been observed for other trace element and metal contaminants such as As and Cd, respectively, as seen in this study and others.

Mercury (Hg) is a highly toxic metal that can bioaccumulate through the food chain—especially in the marine environment—with toxicity related to the chemical form and the route of uptake (Guo et al., 2023). Of the different forms of Hg, methylmercury (MeHg)—a highly toxic form of organic mercury—is the most common in the food chain and is especially common in fish and other seafood products (Banach et al., 2019). The presence of mercury in the environment is from both natural and anthropogenic sources. Natural sources include volcanic activity, erosion of rocks and degassing of the earth's crust, whereas anthropogenic sources include combustion of coal, mining and other industrial activities, fertilizers and waste incineration (Jinadasa et al., 2020). Hg can be responsible for several disorders, including digestive, neurological, immune, cardiac, reproductive as well as genetic (Muñoz and Días, 2020). As is the case for other heavy metals, the levels of Hg in seaweed is dependent on the type of species and sampling location, and in contrast to other heavy metals, the levels of Hg in seaweed are typically low and as such most studies report Hg content as total Hg and these levels are typically below the MLs for feed and edible seaweed (Jinadasa et al., 2020). The findings of the present study confirm this, as Hg (total) was the heavy metal with the lowest concentration of all the non-essential metals in both the wild harvested and cultivated kelps collected from Saldanha Bay, with the recorded values (0.005–0.016 mg.kg^{-1} DW) well below the ML for feed (0.1 mg.kg^{-1}) and edible seaweed (0.1 mg.kg^{-1}) recommended by the European Commission and France, respectively (Table 3). Interestingly, the highest value of Hg was recorded for the wild *Laminaria* collected from Dial Rock (0.0168±0.005 mg.kg^{-1} DW) in Saldanha Bay, whereas the lowest value was recorded for the cultivated *Laminaria* from the same Bay (0.0051±0.0034 mg.kg^{-1} DW). This may suggest that age of the seaweed may play an important role in the levels of accumulation—as it has been shown that faster growing seaweeds accumulate less contaminants and the *Laminaria* analysed in this study was less that 8-months old. Mercury has been described for several edible seaweeds, with higher concentrations generally reported from the brown seaweeds than the red seaweeds (Banach et al., 2019). The levels of Hg recorded in the present study are analogous to levels reported for other brown seaweeds, which range from 0.001 to 0.057 mg.kg^{-1} DW (Besada et al., 2009). Similarly, Hwang et al. (2010) determined Hg concentrations in 426 samples of seaweed sold in Korea during the period of 2007–2008 and reported concentrations of Hg ranging from 0.001 to 0.050 mg.kg^{-1} DW (average of 0.011 mg.kg^{-1} DW), with none of these samples exceeding the ML of 0.5 mg.kg^{-1} DW for fish, molluscs and shellfish in Korea.

Iodine (I) is an essential trace mineral—not made by the body so must be obtained by food or supplements—for both humans and animals and is required for the synthesis of the thyroid hormones triiodothyronine (T3) and thyroxine (T4) which play vital roles in metabolism, embryogenesis and neurological development (Jinadasa et al., 2020; Guo et al., 2023). Iodine is found naturally in certain foods, particularly marine food, such as fish, shellfish and seaweeds—because of the greater iodine concentration in sea water compared to fresh water—which are regarded as a vital source of this mineral (Mann and Truswell 2017; Guo et al., 2023). Iodine deficiency is a major international health concern and because of its importance, iodine is added to table salt and frequently added to food supplements. Insufficient iodine leads to a reduction in thyroid hormones, resulting in an under-active or overactive thyroid gland that causes the medical conditions of hypothyroidism and hyperthyroidism. Deficiencies can prevent normal growth and development and increases the risk of mental retardation, lowered cognitive function and decreased work productivity (Muñoz and Días, 2020). On the other hand, excessive consumption of iodine can be detrimental for people with sensitivity to iodine causing hyperthyroidism or hypothyroidism—which has been documented in countries, such as Japan, where seaweeds are traditionally used as food (Guo et al., 2023). In France, the recommended ML of iodine was set at 2000 mg.kg^{-1} DW for all species of edible seaweed in 2009, whereas Germany has set a ML of 20 mg.kg^{-1} iodine for dried macroalgae products (Guo et al., 2023; ANSES, 2018; CEVA, 2014; AFSSA, 2009). Seaweeds are considered as an iodine-rich material, and generally the iodine content of the Phaeophyceae>Rhodophyta>Chlorophyta, although some green algae, such as *U. clathrata*, and red algae, such as *Gracilaria* spp., have been shown to have a high iodine content (Muñoz and Días, 2020). It has been suggested that the biological role of iodide in seaweed is its activity as an inorganic antioxidant that readily scavengers a variety of reactive oxygen species that are produced due to sunlight and biofilms on the surface of the seaweed (Küpper et al., 2008).

The iodide content of the *M. pyrifera* and *L. pallida* analysed from Saldanha Bay in this study was 1240±230 and 5340 mg.kg^{-1} DW, respectively (data not shown in table). These values are similar to the content of iodine detected in the wild harvested kelps collected and analysed from Kommetjie, SA, by Darias et al. (*unpublished data*) (1068-2423 mg/kg DW) and are similar to what has been reported for other brown seaweeds (1612–6568 mg/kg DW) (Banach et al., 2019; Wang et al., 2021). Aakre et al. (2021) demonstrated that the high iodine content in seaweeds, and consequently in certain seaweed-based foods, can lead to iodine intakes that often surpass the recommended daily levels when consumed. However, because the effect is reversable and reports of its clinical symptoms are rare, a high intake of iodine over a short period of time is considered unlikely to cause adverse health effects. Moreover, it has been shown that various commonly adopted seaweed preparation methods, such as boiling, soaking and blanching, can significantly (>90%) reduce the iodine content of seaweed prior to consumption (FAO, 2021).

Fatty acid content

The fatty acid (FA) content of the *Macrocystis pyrifera* and *Laminaria pallida* cultivated in Saldanha Bay is shown in Table 4, together with the FA profile of wild collected *M. pyrifera*, *Codium fragile* and *Gracilaria chilensis* from Chile, which was included in the table for comparative purposes. Seaweeds typically have a low-fat content, often less than 1 gram per 100 grams, as was the case for the cultivated *M. pyrifera* (0.780±0.091 g.100g^{-1} DW) and *L. pallida* 0.78±0.09 g.100g^{-1} DW) analysed from Saldanha Bay (Table 1). In general, the fatty acid content was higher in the cultivated *M. pyrifera* from Saldanha Bay than in the cultivated *L. pallida* (Table 4). Since both these seaweeds were cultivated at the same site, but harvested a year apart from one another, but at the same time of the year, the differences in FA content could be attributed to genetic differences between the species. The content of polyunsaturated fatty acids (PUFAs)—*Macrocystis* 46.7±5.0 % & *Laminaria* 44.2±5.5 %—were shown to be the most abundant of the FA's followed by the saturated fatty acids (SFAs)—*Macrocystis* 34.7±5.3 % & *Laminaria* 39.5±4.9 %—and monounsaturated fatty acids (MUFAs)—*Macrocystis* 18.4±3.5 % & *Laminaria* 16.3±3.0 %. This finding differs from the Campos et al. (2022) study as well as others (Rohani-Ghadikolaei et al., 2012; Maehre et al., 2014) that have shown that SFA's are the most abundant FA in most seaweeds. The most abundant SFA recorded from both *M. pyrifera* and *L. pallida* cultivated in Saldanha Bay was 16:0 (Palmitic acid), which accounted for 20.6±4.7 % and 17.1±3.9 % of the total fatty acid methyl esters for the *Macrocystis* and *Laminaria*, respectively. This SFA was also shown to be abundant in the three seaweeds analysed form Chile (Ortiz et al., 2009; Table 4) as well as in the four edible seaweed species (*Chondrus crispus*, *Palmaria palmata*, *Porphyra* sp., and *Ulva* sp.) analysed by Campos et al. (2022) from the IMTA system in Portugal. This is not surprising, as it is one of the most common fatty acids found in humans, plants and microorganisms (Carta et al., 2017). Of the monounsaturated fatty acids (MUFAs), 18:1n-9c (oleic acid) was most abundant in the seaweeds analysed by Ortiz et al. (2009) as well as the kelps analysed in this study from Saldanha Bay (Table 4).

M. pyrifera and *L. pallida* from SA also displayed a high content of the polyunsaturated fatty acids (PUFAs) 20:4n-6 (arachidonic acid; 16.1±3.6 & 16.9±3.8 % for *M. pyrifera* and *L. pallida*, respectively) and 20:5n-3 (eicosapentaenoic acid (EPA); 12.8±2.9 % in *M. pyrifera*), while the content of DHA (22:6n-3) was much lower (2.95±0.67 %).

Table 4. Fatty acid composition of *Macrocystis pyrifera* and *Laminaria pallida* cultivated in Saldanha Bay in SA versus *Codium fragile*, *Gracilaria chilensis* and *Macrocystis pyrifera* collected from the wild in Chile (Ortiz et al., 2009).

Fatty Acid	**Methyl Ester [%]**				
	Codium fragile **[Chile, wild harvested]**	***Gracilaria chilensis*** **[Chile, wild harvested]**	***Macrocystis pyrifera*** **[Chile, wild harvested]**	**Macrocystis pyrifera [Saldanha Bay, cultivated]**	***Laminaria pallida*** **[Saldanha Bay, cultivated]**
SFA					
12:0	0.30±0.01	0.35±0.02	-	-	-
14:0	1.04±0.05	2.05±0.06	0.73±0.01	9.4±2.20	7.9±1.80
15:0	0.66±0.01	0.43±0.01	0.36±0.01	0.61±0.17	0.27±0.10
16:0	17.74±0.09	21.84±0.10	16.17±0.06	20.6±4.7	17±3.90
17:0	1.11±0.12	0.47±0.00	-	0.48±0.14	0.47±0.14
18:0	17.38±0.04	9.17±0.05	3.05±0.11	2.62±0.60	0.98±0.24
20:0	0.82±0.00	0.70±0.02	0.59±0.09	1.03±0.25	0.23±0.09
22:0	2.52±0.06	0.77±0.09	1.30±0.16	-	-
24:0	1.91±0.01	0.93±0.04	0.58±0.18	-	9.4±2.2
MUFA					
14:1	-	0.15±0.00	-	-	-
15:1	1.51±0.03	-	0.72±0.02	-	-
16:1	2.30±0.02	5.84±0.13	0.99±0.01	2.46±0.56	3.07±0.69
17:1	-	1.89±0.06	-	-	-
18:1n-9t	3.02±0.01	1.58±0.03	0.94±0.02	-	0.44±0.13
18:1n-9c	12.25±0.10	29.02±0.18	19.64±0.08	14.70±3.3	11.9±2.8
18:1n-7c	0.87±0.03	3.01±0.02	1.23±0.01	1.00±0.94	0.16±0.00
20:1	-	-	0.91±0.00	0.26±0.11	0.75±0.19
22:1	-	-	0.74±0.00	-	-
PUFA					
16:2	-	-	1.19±0.08	-	-
18:2	-	8.14±0.01	0.39±0.00	3.41±0.77	3.76±0.85
18:2n-6	6.24±0.18	9.65±0.09	43.41±0.39	-	-
18:3n-3	24.56±0.24	0.68±0.01	5.45±0.00	3.60±0.81	7.4±1.7

18:4n-3	1.11±0.02	1.00±0.00	-	6.4±1.5	15.0±3.5
20:4n-6	2.56±0.01	0.53±0.02	0.50±0.05	16.1±3.6	16.9±3.8
20:5n-3	2.10±0.00	1.30±0.01	0.47±0.01	12.8±2.9	-
22:6n-3	-	-	-	2.95±0.67	-

Eicosapentaenoic acid is an Omega-3 fatty acid that has been shown to play an important role in anti-inflammatory, anti-thrombotic and anti-arrhythmic (cardiac arrythmia) responses—hence this species may provide numerous health benefits following consumption. Interestingly, both EPA and DHA were not detected in the cultivated *L. pallida*.

This is in agreement with previous studies that have shown that brown algae (e.g., *Laminaria* sp., *Undaria* sp., *Hizikia* sp.) have low concentrations of EPA, typically 5.9–13.6 % of total FAME, and the content of DHA in species of *Porphyra*, *Laminaria* and *Undaria*, are generally below the limit of detection (less than 0.1 % of total FAME) (Fleurence et al., 1994; Takagi et al., 1985). Conversely, these seaweed species often have high concentration of oleic acid, with 4.1–20.9 % of total FAME (Dawczynski et al., 2007), as was the case for the two kelps analysed in this study (Table 4).

Other elements

Pesticide residues frequently enter the environment from agricultural practices but could also occur in seaweeds from the use of plant protection products—although the latter is less likely to occur with the current size of the industry, lack of rivers entering the Saldanha Bay/ Langebaan system and considering kelps are cultivated on rope structures in an open water system in Saldanha Bay (FAO and WHO 2012). There is unfortunately limited information on the monitoring of pesticide residues and the subsequent regulatory limits for edible seaweeds globally. Consequently, the EU has set a default maximum residue limit (MRL) of 0.01 $mg.kg^{-1}$ for most pesticides (Banach et al., 2019; FAO and WHO 2012). Of the ca. 950 pesticides tested for in the current study, only two were detected in the South African kelps, Tribromoanisole and Tribromophenol. Tribromophenol occurred in all seaweeds (wild and cultivated) analysed from Saldanha Bay, whereas Tribromoanisole only occurred in the wild harvested *E. maxima* (Table 5). None of the other pesticides tested for were detected in this study.

The tribromophenol concentration was highest in the *L. pallida* (0.663±0.279 $mg.kg^{-1}$ DW) cultivated in Saldanha Bay close to the mussel raft structures, with the second highest content recorded from the *L. pallida* (0.500±0.211 $mg.kg^{-1}$ DW) collected from the natural population in the vicinity of Dial Rock, followed by the cultivated *M. pyrifera* (0.266±0.113 $mg.kg^{-1}$ DW). The wild harvested *E. maxima* (0.082±0.035 $mg.kg^{-1}$ DW) collected from the vicinity of Club Mykonos had the lowest content of this pesticide. The concentration of both these compounds was above the MRL (0.01 $mg.kg^{-1}$ DW) set by the EU. Tribromophenol is a brominated derivative of phenol that is used as a fungicide, wood preservative, and as an intermediate in the preparation of flame retardants. Tribromoanisole is a brominated derivative of anisole and is a fungal metabolite that is also used as a fungicide. Both compounds are natural metabolites of various marine species, especially seaweeds, can be produced by naturally occurring fungi or bacteria or may enter the environment from anthropogenic sources such as leaching from wood preservatives (e.g., shipping pallets treated by bromophenols) (Dron et al., 2022). Other major sources of these compounds are contamination of marine waters and organisms resulting from brominated flame retardants and pesticides; but these compounds have also been identified as a by-product of the chlorination of bromide-rich seawater and wastewater—in wastewater treatment plants—that enter the marine environment (Dron et al., 2022).

The source of these two pesticides, detected in the kelps from Saldanha Bay, remains unclear, but their presence should be carefully monitored in the kelps cultured in the Bay to determine whether they will be present in the cultured species throughout the year and in different locations of the Bay (as the industry expands). This will help provide more insight on seasonal and/or natural levels as well as the possible sources of these pesticides.

Persistent organic pollutants, such as dioxins and polychlorinated biphenyls (PCBs), are pollutants with high chemical stability and are known to accumulate in fatty tissues of animals. Although the lipid content of seaweed is generally low (1–6 g.100 g^{-1} DW), seaweeds do accumulate these pollutants. For example, *Ulva rigida* can rapidly assimilate PCBs and *U. rigida* that was placed in a contaminated harbour was shown to have a PCB content of 3.9 $mg.kg^{-1}$ DW after just 1 day (Cheney et al., 2014). There is currently no maximum regulatory limit for PCBs in edible seaweeds. However, for feed the "EU MLs established for dioxins, the sum of dioxins and dl-PCBs, and ndl-PCBs are 0.75 ng WHOPCDD/ F-TEQ/kg, 1.25 ng WHO-PCDD/F-PCB-TEQ/kg, and 10 $\mu g.kg^{-1}$, respectively (EU, 2002)" (Banach et al., 2019).

Table 5. Polyfluorinated Alkyl Substance (PFAS), dioxin and dioxin-like Polychlorinated bisphenols (PCBs), Polychlorinated Dibenzodioxins/Furans (PCDDs/PCDFs), polycyclic Aromatic Hydrocarbons (PAH), and the pesticide composition of wild harvested *Laminaria pallida* and *Ecklonia maxima* collected from three sites in Saldanha Bay as well as the *M. pyrifera* and *L. pallida* cultivated at Blue Ocean Mussel farm in Saldanha Bay Western Cape Province, SA.

HAZARD	**SPECIES AND LOCALITY IN SALDANHA BAY**				
	Laminaria pallida, Dial Rock [Wild harvested]	*Ecklonia maxima,* Club Mykonos [Wild harvested]	*Ecklonia maxima,* Die Strandloper [Wild harvested]	*Macrocystis pyrifera,* BOM & Viking, Saldanha Bay [Cultivated]	*Laminaria pallida,* BOM, Saldanha Bay [Cultivated]
POLYFLUORINATED ALKYL SUBSTANCES (PFAS) [$ug.kg^{-1}$]	**Value**	**Value**	**Value**	**Value**	**Value**
PFOS (sum of branched and linear isomers)	0,057±0,026	n.d.	0,027±0,012	n.d.	0.01 – 0.02
PFOA (sum of branched and linear isomers)	n.d.	n.d.	n.d.	n.d.	n.d.
PFNA (sum of linear PFNA and branched isomers)	n.d.	n.d.	n.d.	n.d.	n.d.
PFHxS (sum of linear PFHxS and branched isomers)	n.d.	n.d.	n.d.	n.d.	n.d.
Somma di PFOS, PFOA, PFNA e PFHxS (sum of linear and branched isomers)	0,057±0,026	<0,020	0,027±0,012	<0.020	<0.020
Perfluorobutanoic acid (PFBA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluoropentanoic acid (PFPeA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorohexanoic acid (PFHxA)	traces	n.d.	0,024±0,011	n.d.	n.d.
Perfluoroheptanoic acid (PFHpA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorodecanoic acid (PFDA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluoroundecanoic acid (PFUnDA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorododecanoic acid (PFDoDA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorotridecanoic acid (PFTrDA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorotetradecanoic acid (PFTeDA)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorobutanesulfonic acid (PFBS)	n.d.	n.d.	n.d.	n.d.	n.d.

Perfluoropentanesulfonic acid (PFPS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluoroheptanesulfonic acid (PFHpS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorononanesulfonic acid (PFNS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorodecanesulfonic acid (PFDS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluoroundecansulfonic acid (PFUnDS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorododecansulfonic acid (PFDoDS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorotridecanesulfonic acid (PFTrDS)	n.d.	n.d.	n.d.	n.d.	n.d.
Perfluorooctane sulphonamide (FOSA)	n.d.	n.d.	n.d.	n.d.	n.d.
9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid (F53B)	n.d.	n.d.	n.d.	n.d.	n.d.
11-chloroeicosafluoro-3-oxaundecane-1--sulfonic acid (F53B-MINOR)	n.d.	n.d.	n.d.	n.d.	n.d.
Undecafluoro-2-methyl-3-oxahexanoic acid (GENX)	n.d.	n.d.	n.d.	n.d.	n.d.
Dodecafluoro-3h-4,8-dioxanonanoic acid (ADONA)	n.d.	n.d.	n.d.	n.d.	n.d.
Capstone A (DPOSA)	n.d.	n.d.	n.d.	n.d.	n.d.
Capstone B (CDPOS)	n.d.	n.d.	n.d.	n.d.	n.d.
6:2 fluorotelomer sulfonic acid (6:2 FTS)	0,022±0,010	n.d.	n.d.	n.d.	n.d.
DIOXINS AND DIOXINS-LIKE PCB (HIGH RESOLUTION) DIOXIN-LIKE PCBs [pg.g^{-1}]	**Value**	**Value**	**Value**	**Value**	**Value**
(81) 3,4,4',5-TetraCB	n.d.	Traces	n.d.	n.d.	n.d.
(77) 3,3',4,4'-TetraCB	0,122±0,048	0,112±0,046	0,095±0,042	0.82±0.26	0.097±0.043
(123) 2',3,4,4',5-PentaCB	0,32±0,11	n.d.	traces	0.48±0.16	0.017 – 0.050
(118) 2,3',4,4',5-PentaCB	2,99±0,94	1,56±0,49	1,49±0,47	8.4±2.6	1.46±0.46
(114) 2,3,4,4',5-PentaCB	n.d.	Traces	n.d.	n.d.	0.017 – 0.050
(105) 2,3,3',4,4'-PentaCB	0,75±0,24	0,46±0,15	0,57±0,19	2.7±0.083	0.49±0.16
(126) 3,3',4,4',5-PentaCB	n.d.	n.d.	n.d.	n.d.	n.d.
(167) 2,3',4,4',5,5'-HexaCB	0,179±0,064	0,052±0,034	0,090±0,041	0.53±0.17	0.077±0.038
(156) 2,3,3',4,4',5-HexaCB	0,294±0,097	0,126±0,050	0,187±0,066	0.87±0.28	0.139±0.053
(157) 2,3,3',4,4',5'-HexaCB	0,064±0,036	n.d.	traces	0.247±0.083	0.017 – 0.050
(169) 3,3',4,4',5,5'-HexaCB	n.d.	n.d.	n.d.	n.d.	n.d.
(189) 2,3,3',4,4',5,5'-HeptaCB	n.d.	n.d.	n.d.	0.128±0.050	n.d.
PCBs WHOTEQ (Upper Bound)	0,007±0,003	0,007±0,004	0,007±0,004	0.007±0.003	0.007±0.004
NO DIOXIN-LIKE PCBs [pg.g^{-1}]	**Value**	**Value**	**Value**	**Value**	**Value**
(28) 2,4,4'-TriCB	8,4±3,1	4,8±2,7	6,7±2,9	6.6±2.9	6.6±2.9
(52) 2,2',5,5'-TetraCB	4,8±2,7	Traces	traces	4.4±2.7	1.3 – 4.0
(101) 2,2',4,5,5'-PentaCB	traces	Traces	traces	5.8±2.8	1.3 – 4.0
(138) 2,2',3,4,4',5'-HexaCB	traces	Traces	traces	10.5±3.4	1.3 – 4.0
(153) 2,2',4,4',5,5'-HexaCB	7,1±3,0	Traces	traces	16.2±4.2	1.3 – 4.0
(180) 2,2',3,4,4',5,5'-HeptaCB	traces	n.d.	n.d.	5.1±2.8	n.d.
Non-dioxin-like PCBs (sum of 6 congeners: 28, 52,101, 138, 153, and 180) as ng.g^{-1}	0,0323±0,0069	0,0248±0,0066	0,0267±0,0067	0.0486±0.0078	0.0266±0.0067
POLYCHLORINATED DIBENZODIOXINS/FURANS (PCDDs/PCDFs) TOXIC CONGENERS CONSIDERED BY OMS PCDDs 2,3,7,8 SUBSTITUTED [pg.g^{-1}]	**Value**	**Value**	**Value**	**Value**	**Value**
2,3,7,8-TetraCDD	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,7,8-PentaCDD	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,4,7,8-HexaCDD	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,6,7,8-HexaCDD	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,7,8,9-HexaCDD	n.d.	n.d.	n.d.	n.d.	n.d.

1,2,3,4,6,7,8-HeptaCDD	0,038±0,019	Traces	n.d.	0.106±0.036	0.038±0.019
OctaCDD	0,186±0,060	0,054±0,022	0,223±0,071	0.67±0.21	0.138±0.046
PCDFs 2,3,7,8 SUBSTITUTED [pg.g^{-1}]	**Value**	**Value**	**Value**		
2,3,7,8-TetraCDF	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,7,8-PentaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
2,3,4,7,8-PentaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,4,7,8-HexaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,6,7,8-HexaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
2,3,4,6,7,8-HexaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,7,8,9-HexaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,4,6,7,8-HeptaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
1,2,3,4,7,8,9-HeptaCDF	n.d.	n.d.	n.d.	n.d.	n.d.
OctaCDF	n.d.	n.d.	n.d.	n.d.	0.027±0.017
Sum of dioxins (WHOPCDD/FTEQ)	0,079±0,025	0,079±0,025	0,079±0,025	0.080±0.025	0.079±0.025
Dioxins and dioxin-like PCBs sum (WHO-PCDD/F-PCBTEQ)	0,086±0,025	0,086±0,025	0,086±0,025	0.087±0.025	0.086±0.025
POLYCYCLIC AROMATIC HYDROCARBONS (PAHs) [ug.kg^{-1}]	**Value**	**Value**	**Value**		**Value**
Benzo (a) anthracene	n.d.	n.d.	n.d.		n.d.
Benzo (b) fluoranthene	n.d.	n.d.	n.d.	n.d.	n.d.
Benzo (k) fluoranthene	n.d.	n.d.	n.d.	n.d.	n.d.
Benzo (a) pyrene	n.d.	n.d.	n.d.	n.d.	n.d.
Indeno (1,2,3-CD) pyrene	n.d.	n.d.	n.d.	n.d.	n.d.
Dibenzo (a,h) anthracene	n.d.	n.d.	n.d.	n.d.	n.d.
Benzo (g,h,i) perylene	n.d.	n.d.	n.d.	traces	n.d.
Benzo (e) pyrene	n.d.	n.d.	n.d.	n.d.	n.d.
Chrysene	n.d.	n.d.	n.d.	traces	n.d.
PAHs 4	<0,50	<0,50	<0,50	<0.50	<0.50
PESTICIDES [mg.kg^{-1}] *Only those pesticides that were detected, out of the 950 compounds analysed for in the study, are presented below.	**Value**	**Value**	**Value**	**Value**	**Value**
Tribromoanisole	n.d.	0,082±0,035	0,059±0,025	n.d.	
Tribromophenol	0,500±0.211	0,082±0,035	0,016±0,007	0,266±0,113	0,663±0,279

In the present study, several dioxin and dioxin-like PCBs were detected. The concentration of non-dioxin-like PCBs was generally higher for all kelps analysed from the Bay, compared with the dioxin-like PCBs, with values for wild harvested *L. pallida* and *E. maxima* as well as the cultivated *L. pallida* appearing similar, whereas the cultivated *M. pyrifera* appeared to exhibit the highest values for many of the compounds, particularly the non-dioxin-like PCBs (Table 5). Out of the 19 PCBs monitored for in the kelps, 16 were detected in the cultivated *M. pyrifera* and ranged in concentration from 0.007–8.4 pg.g^{-1} DW, whereas 14 were detected in the cultivated *L. pallida* and ranged in concentration from 0.007–6.6 pg.g^{-1} DW. However, more than 99% of the PCBs were below the cancer slope factor (CSF) limit from the USEPA Integrated Risk Information System database [8 ug.kg^{-1} DW]. Since the presence of dioxin and dioxin-like PCBs is determined by the seaweed cultivation environment as well as the accumulation capacity in the seaweed, levels of these compounds should be carefully monitored for all species cultivated at sites in Saldanha Bay over different seasons to determine the presence and concentration of potential PCBs.

Trace element and heavy metal content of pre-processed kelps

In the present study, the effects of two blanching methods—2-minutes of boiling or 20-minutes of steaming followed immediately by 5-minutes of rapid cooling in ice water—on the heavy metal (Cd, Pb and Hg), As and I content of *E. maxima*, *M. pyrifera* and *L. pallida* were investigated. These two variations of blanching were selected as they have previously been shown to reduce the content of certain critical elements, particularly iodine, in selected seaweeds (Nitschke and Stengel, 2016; FAO, 2022; Guo et al., 2023).

For example, Nitschke and Stengel (2016) demonstrated that steaming and blanching can reduce the iodine content in seaweed products by as much as 58 %, compared with washing (10 %) and soaking (34-44 %). Moreover, blanching does not require any specialized equipment and is simple/easy enough to be implemented in most household food preparation steps or low-tech industrial processes.

We demonstrated that both boiling and steaming can significantly reduce the iodine content of all three South African kelps and that the extent of the reduction was species dependent (Figure 2). Of the two methods, boiling was more effective for reducing iodine content, resulting in a reduction of 83.87 % ($P=0.004$), 58.92 % ($P<0.001$) and 70.37 % ($P<0.001$) for *Ecklonia, Laminaria* and *Macrocystis*, respectively (Figure 2). Conversely, steaming reduced the iodine contents by 32.90 %, 12.51 % and 53.52 % for the *Ecklonia, Laminaria* and *Macrocystis*, respectively. These findings support previous studies that have shown that blanching can significantly reduce the content of iodine in seaweed and that the level of reduction varies between seaweed species (Nitschke and Stengel, 2016; Guo et al., 2023; Blikra et al., 2024). The effects of both pre-processing treatments were however not as pronounced for the other elements/metals, with no significant reduction observed in the content of As, Hg, Cd and Pb for either boiling or steaming for any of the kelps. In fact, for the *Macrocystis* we recorded a significant increase in the content of Hg, Cd and Pb after steaming blades for 20-minutes, when compared with the control treatment. There was also a similar significant increase in the content of Cd and Pb following boiling for 2-minutes. Similar observations were made by Blikra et al. (2024) following processing of sugar kelp (*Saccharina latissima*) by pulsed electric field (PEF) processing and soaking/blanching treatments (at 10, 45, and 60 ºC). In their study, blanching in the pre-tempered water reduced the iodine content in S. latissima by 90 %, which is much higher than previously reported values in kelps—with reductions of 59 to 95 % previously reported for sugar kelp. However, the Cd concentration in the sugar kelp increased by 114 % following blanching. Blikra et al. (2024) suggested that this may be due to concentration of the metal in the remaining biomass of the seaweed—due to the extraction of other dry matter components during processing. It is therefore possible that the metals Hg, Cd and Pb recorded in the present study are also being concentrated in the remaining biomass of *Ecklonia, Laminaria* and *Macrocystis* during processing, but this needs to be investigated further. Additionally, other methods and/or variations of the existing methods of processing need to be explored to find a suitable method(s) for reducing the content of toxic heavy metals in South African kelps. For example, Hanaoka et al. (2001) demonstrated that washing and soaking the brown seaweed *Sargassum fusiforme* (Hijiki) decreases its total arsenic content by ca. 60 %. Nitschke & Stengel (2016) showed that washing and dehydration can lower the iodine content of some edible seaweeds (e.g., *Alaria esculenta*), but when followed by rehydration (1-24hr soaking in deionised water) iodine content reduced further by 62 % in *A. esculenta*, by 15 % in *Palmaria palmata* and by 10 % in *Ulva intestinalis*. Since the effects of different processing techniques on the content of heavy metals in different seaweed species vary (Blikra et al., 2022) and limited information exists for South African kelps, further investigations are required.

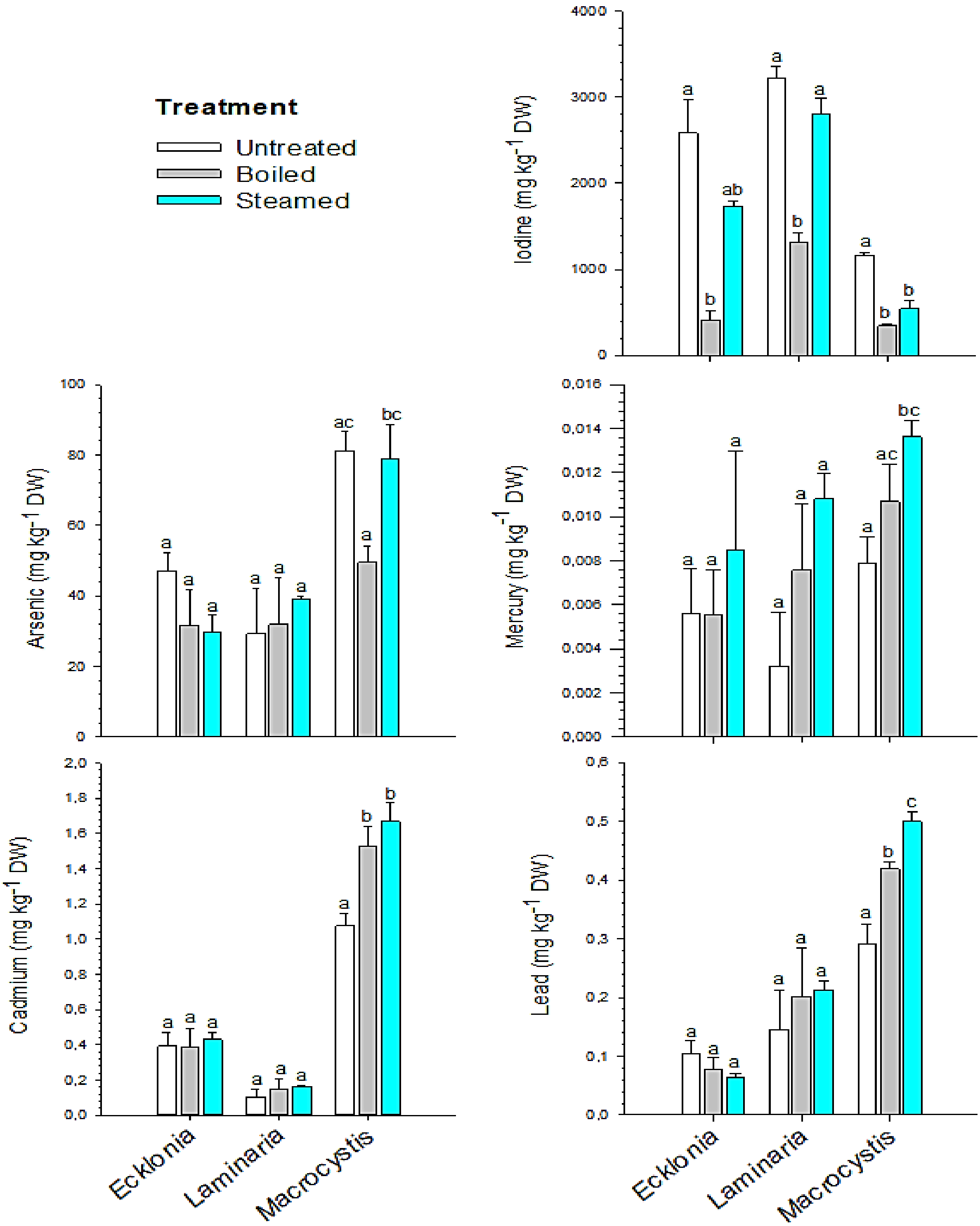

Figure 2. Effects of two blanching methods—2-minutes of boiling or 20-minutes of steaming followed immediately by 5-minutes of rapid cooling in ice water—on the heavy metal (Cd, Pb and Hg), As and I content of *E. maxima*, *M. pyrifera* and *L. pallida*. (Graph credit: Dr BM Macey)

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