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Value Added Product Development in Marine Biotechnology

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Content

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Overview

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Key Definitions

- Marine biotechnology, also known as blue biotechnology, is broadly defined as the application of science and technology to living organisms from marine resources, or parts, products, or models derived from them, for the production of knowledge, goods, and services (Daniotti et. al 2021 & Freitas et. al. 2012).

Application

- Pharmaceutical and Biomedical Industries
- Food and Nutraceutical Industries
- Biofuels and Energy
- Industrial Enzymes
- Bioremediation and Environmental Monitoring
- Cosmetic Industry
- Agronomy

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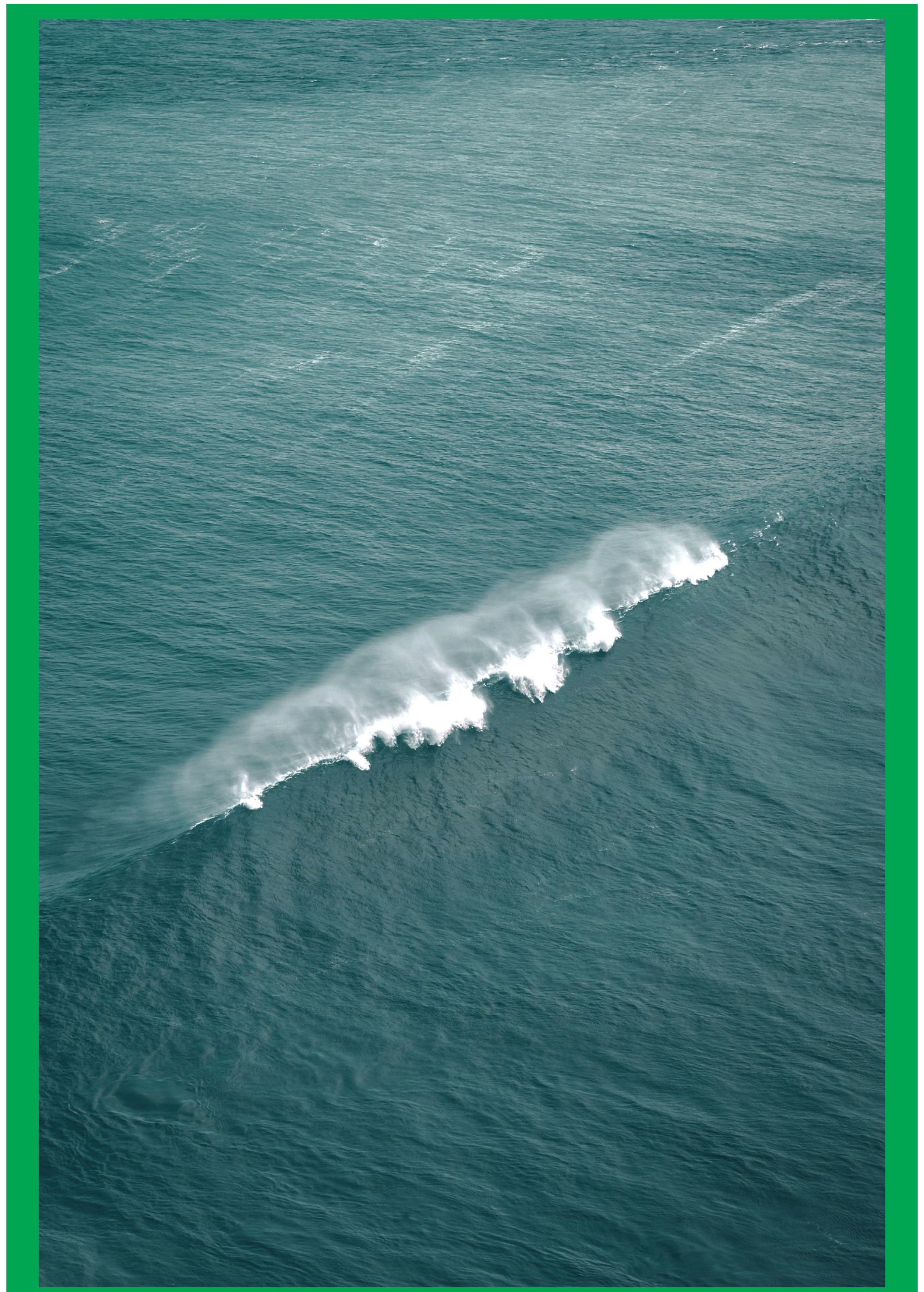
Potential

- **The marine environment covers 70% of Earth's surface** and is home to an estimated over a million macroscopic species and approximately one billion species of microorganisms. **The vastness and largely unexplored nature of the oceans mean that 91% of marine species are yet to be classified.**
- Many products from marine invertebrates have potential as drugs, with almost 10,000 new molecular entities identified between 1990 and 2009.
- **The marine biotechnology market is showing a positive development trend,** with scientific publications more than doubling from 2010 to 2019. Significant growth is projected, **with an estimated incremental growth of $2.5 billion from 2020 to 2024 globally, and over $1.3 billion in Europe, with pharmaceutical and food sectors accounting for more than 60% of the market value.**



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Potential in Pharmaceutical and Biomedical Industries

Drugs:
Specific drugs derived from marine biodiversity include trabectedin (an antitumor drug from sea squirts), vidarabine (an antiviral from marine sponges), cytarabine (an antileukemia agent from sponges), and ziconotide (an analgesic from cone snails).

Antibiotics and Antimicrobials:
Marine fungi have yielded numerous antibacterial and antifungal compounds, including cephalosporins.

Anti-cancer Agents:
- Marine-derived compounds like Salinosporamide A (marizomib) from *Salinispora tropica* are in Phase III clinical trials as anticancer agents
- marinomycins A-D and compounds from *Streptomyces sp.*, show potent cytotoxicity against cancer cell lines.
- The nucleosides spongothymidine and spongouridine from the marine sponge *Cryptotethia crypta* formed the basis for Ara-C, an early marine-derived anticancer agent.

Other Therapeutic Applications:
Marine organisms can provide compounds for treating various conditions, such as anti-inflammatory agents (e.g., Cyclomarin A from marine bacteria and molecules that inhibit osteoclastogenesis for osteoporosis treatment, as seen with fermented Pacific oyster extracts.

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Potential in Pharmaceutical and Biomedical Industries

Medical Devices and Biomaterials:
Collagen extracted from jellyfish can be used for medical devices and biomaterials like scaffolds and hydrogels for wound healing and regenerative medicine. Fish-derived gelatin is an alternative to bovine/porcine gelatin in medical devices, offering higher safety standards. Bioactive ceramic materials from corals, shells, and sea urchins are sources for hydroxyapatite synthesis for bone structures.

Bio-inspired Materials:
highly ordered inorganic–organic composite materials from sponge silica-forming enzymes (silicateins) and nanostructured biosilica shells (frustules) from diatoms for high-tech products like microelectronics.

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Potential in Food and Nutraceutical Industries

- **Polysaccharides**, including algins, carrageenans, agar, and sulphated fucans (fucoidans, ulvans), used as **thickeners, stabilizers, and gelling agents** in foods. Some also exhibit antithrombotic, anti-inflammatory, antioxidant, anticancer, and antidiabetic activities, or have potential as **dietary fiber and prebiotic compounds**.
- **Pigments** like carotenoids (e.g., astaxanthin, fucoxanthin, β-carotene) and chlorophylls. These act as vitamin precursors, antioxidants, and anti-carcinogenic agents, and are used as food colorants and antioxidants. The SMILE project developed a microalgae extract rich in fucoxanthin and omega-3 for weight control and cognitive function. The VOPSA 2.0 project specifically aimed to produce astaxanthin and omega-3 from microalgae for food supplements.
- **Chitin, chitosan, and chitooligosaccharides (COS)**, primarily extracted from crustaceans. These are biodegradable polymers with antibacterial properties, used as **food preservatives** and as anti-cholesterol agents due to their fat-absorbing ability. In Japan, chitosan is added to various foods as a cholesterol-lowering functional ingredient.
- **Minerals and fibers**. The Blue Iodine II project, for instance, focuses on developing iodine-rich algae-based products to combat iodine deficiency.

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Potential in Food and Nutraceutical Industries

- **Omega-3 polyunsaturated fatty acids (PUFAs)**, such as EPA, ARA, and DHA, derived from fish, microalgae, and thraustochytrids, which have proven cardioprotective, antioxidant properties, and benefits for visual and neurological development. The LIFEOMEGA project, for example, developed an EPA-rich nutritional product for cancer patients. Thraustochytrids are recognized as an increasingly important and eco-friendly marine source of PUFAs, offering an alternative to fish oil due to sustainability concerns, typical fishy smell, and poor oxidative stability.
- **Vitamins, proteins, peptides, and amino acids** like taurine, many of which are essential for human health. Protein hydrolysates from fish, for instance, can improve the immune system and are used in health food and nutraceutical industries.
- **Polysaccharides**, including algins, carrageenans, agar, and sulphated fucans (fucoidans, ulvans), used as **thickeners, stabilizers, and gelling agents** in foods. Some also exhibit antithrombotic, anti-inflammatory, antioxidant, anticancer, and antidiabetic activities, or have potential as **dietary fiber and prebiotic compounds**.

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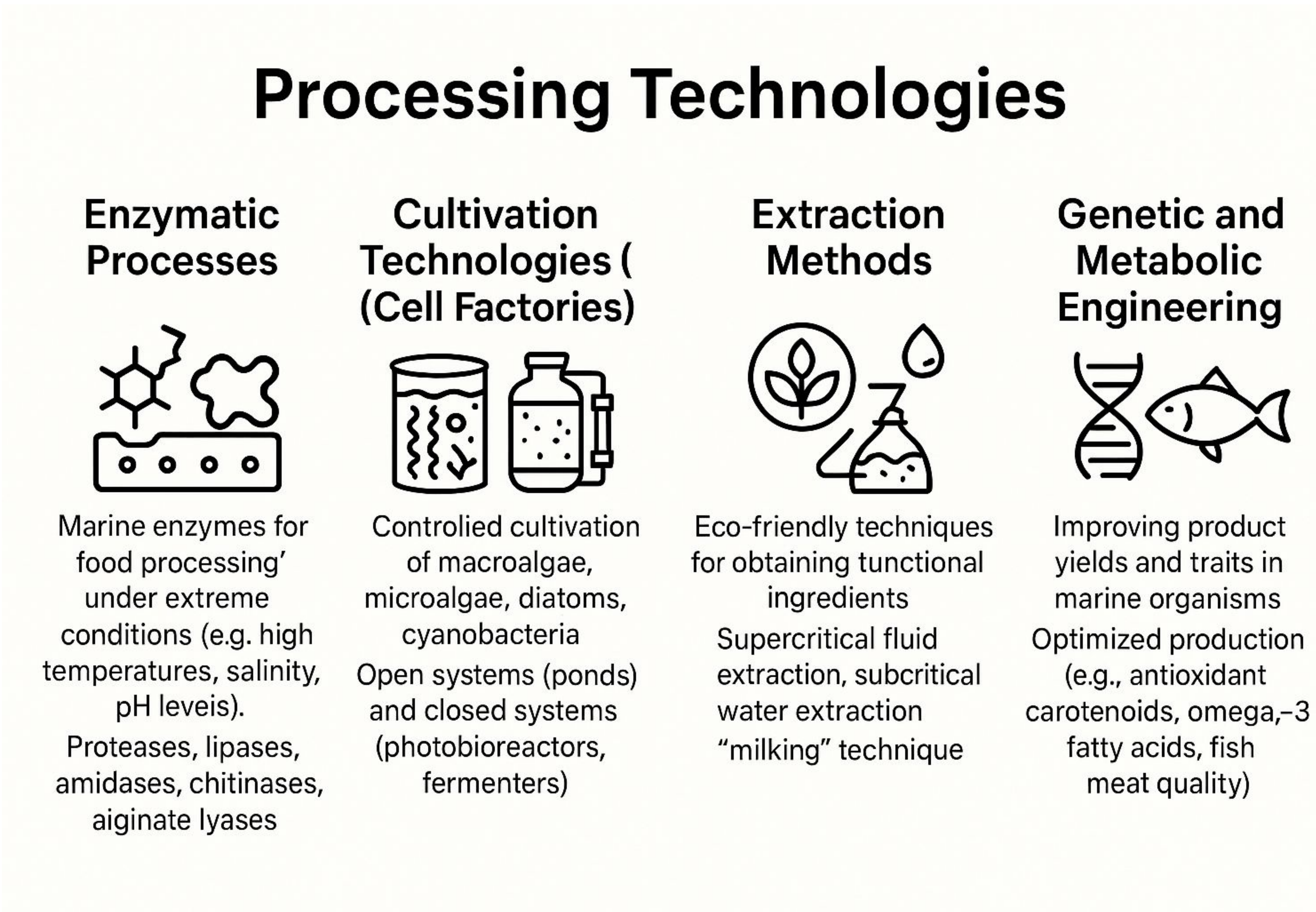
Processing Technologies in Food and Nutraceutical Industries Development



- **Enzymatic Processes**: Marine enzymes are crucial for food processing, offering advantages due to their activity and stability under extreme conditions such as high temperatures, salinity, and various pH levels. They can efficiently convert marine by-products into functional ingredients, offering a more sustainable and cost-effective approach than traditional chemical methods. Examples include proteases, lipases, amidases, chitinases, and alginate lyases.
- **Cultivation Technologies (Cell Factories)**: Macroalgae, microalgae, diatoms, and cyanobacteria are cultivated in both **open systems (ponds)** and **closed systems (photobioreactors or fermenters)**. These methods allow for controlled production of biomass and high-value compounds, with advantages like exploiting solar energy, mitigating air pollutants, and achieving higher productivity and biomass quality in controlled environments. **Heterotrophic and mixotrophic cultivation** in fermenters can offer more controlled and cost-effective processes.
- **Extraction Methods**: Advanced and eco-friendly extraction techniques like **supercritical fluid extraction (SFE) and subcritical water extraction (SWE)** are used to obtain functional ingredients, offering high selectivity and reduced environmental impact compared to conventional methods. The "milking" technique is also being explored for non-destructive, regenerative extraction of metabolites from marine organisms.
- **Genetic and Metabolic Engineering**: These rapidly developing techniques, particularly for microalgae, are used to **improve product yields** and characteristics. They allow for the controlled manipulation of marine organisms to optimize the production of specific compounds. For example, metabolic engineering can enhance the capacity to produce antioxidant carotenoids. Recombinant DNA technologies are also used to increase the productivity of an organism or improve product traits, such as enhancing omega-3 fatty acid production or improving fish meat quality.

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Potential in Cosmetic Industry

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- **Algae (Macroalgae and Microalgae)**: Widely used to extract minerals, fibers, and secondary metabolites like **lipids and carotenoids** for food supplements or nutraceutical additives, which also have cosmetic applications.
  - **Carotenoids** (e.g., astaxanthin, fucoxanthin, β-carotene, lutein) act as **vitamin precursors, antioxidants, and anti-carcinogenic agents**. They are used as **food colorants and antioxidants** and are being explored for their **anti-inflammatory and anti-aging activities**, and for reducing the risk of conditions like diabetes. Specific examples include:
    - Astaxanthin from *Haematococcus pluvialis* is considered a "super antioxidant" with applications in human nutraceuticals and cosmetics. The VOPSA 2.0 project specifically aimed to produce astaxanthin from microalgae for food supplements, with *Neoalgae* developing a cosmetic line, Alskin, including a face cream with astaxanthin-rich *Haematococcus pluvialis* extracts.
    - Fucoxanthin and omega-3 fatty acids from microalgae, as seen in the SMILE project, were developed for a nutraceutical product that also supports cognitive function and weight control, indicating broader health benefits applicable to well-being and appearance.
    - β-carotene from *Dunaliella salina* is another commercially produced pigment from microalgae.

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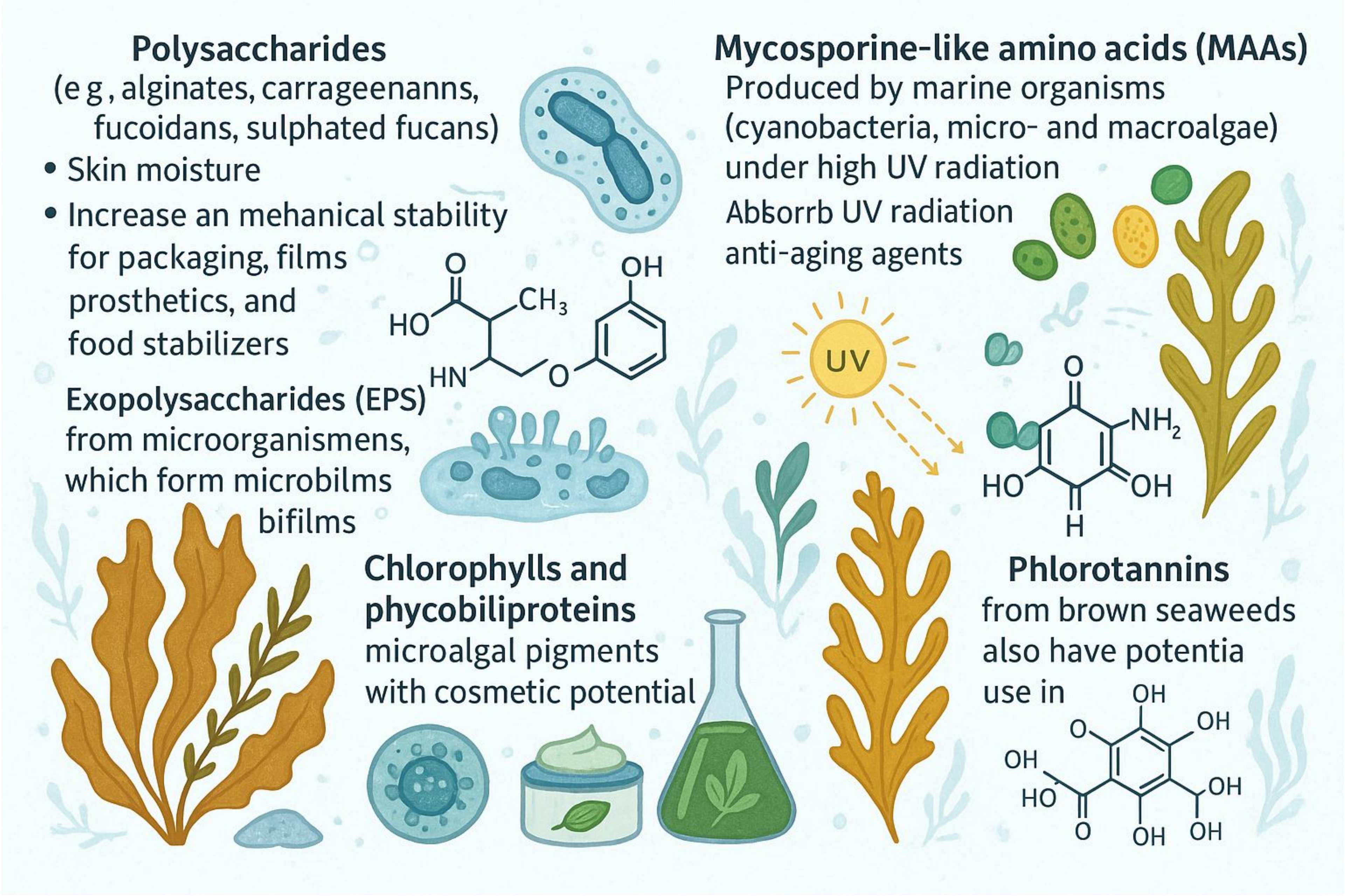
Potential in Cosmetic Industry



- **Polysaccharides** (e.g., alginates, carrageenans, fucoidans, sulphated fucans) are used as **thickeners, stabilizers, and gelling agents**. Some also exhibit **anticoagulant, antibacterial, antiviral, and antifungal activities**. Exopolysaccharides (EPS) from microorganisms, which form the main component of biofilms, can **increase skin moisture** and provide mechanical stability for materials like packaging, films, prosthetics, and food stabilizers.
- **Mycosporine-like amino acids (MAAs)**, produced by marine organisms (cyanobacteria, micro-, and macroalgae) under high UV stress, absorb UV radiation and are considered **photoprotective and anti-aging agents**.
- **Chlorophylls and phycobiliproteins** are also microalgal pigments with cosmetic potential.
- **Phlorotannins** from brown seaweeds also have potential use in cosmetics.

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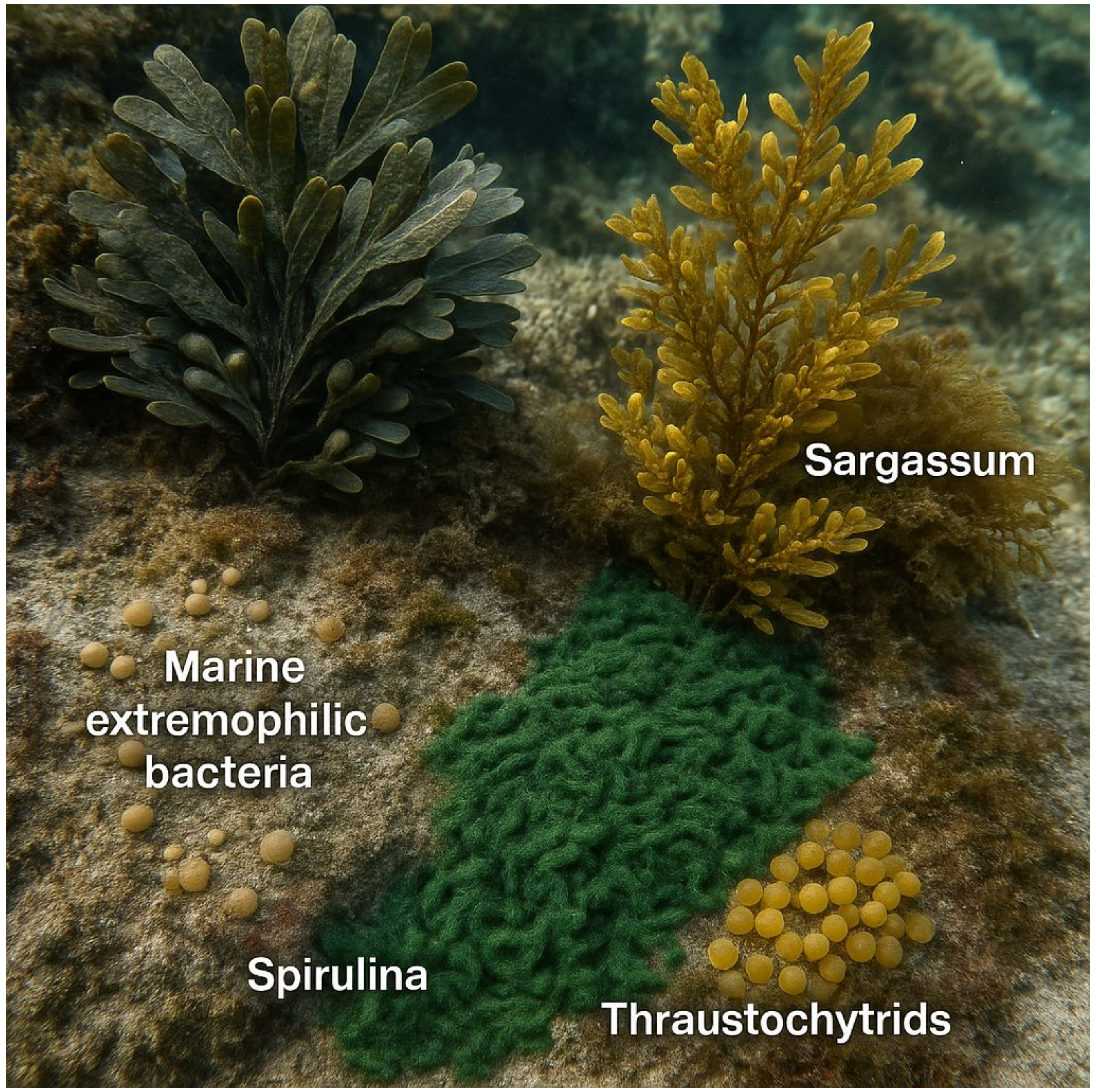
Potential in Cosmetic Industry



- Invasive seaweeds, such as *Fucus* and *Sargassum* species, can be valorized for skincare products, also mitigating adverse effects on local biodiversity.
- **Marine Microorganisms (Bacteria, Fungi, Thraustochytrids, Cyanobacteria)**: These are increasingly recognized as sources of diverse secondary metabolites for cosmetics.
    - Marine extremophilic bacteria, adapted to various extreme marine environments, offer unique properties.
    - Marine fungi are a promising source of pharmacologically active metabolites.
    - Cyanobacteria, like *Arthrospira* (Spirulina), produce diverse bioactive secondary metabolites with **antimicrobial, anti-inflammatory, antioxidant, anticoagulant, anticancer, antiprotozoal, and antiviral activities**, making them suitable for medical, food, and cosmetic applications.

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Potential in Cosmetic Industry

- **Marine Animals and By-products**:
  - **Fish** are a source of **omega-3 polyunsaturated fatty acids** (PUFAs) with cardioprotective and antioxidant properties, also used in cosmetics.
  - **Collagen and gelatin** derived from marine jellyfish and fish by-products are excellent functional ingredients for the cosmetic industry. Jellagen PTY Ltd, for example, markets jellyfish collagen for medical devices and biomaterials.
  - **Chitin** from crustaceans is used as an active ingredient in cosmetics.
  - **Bioactive peptides** from fish and shellfish processing waste can be used in nutraceuticals and pharmaceuticals. Peptides derived from *Chlorella* have shown protective effects against UV-induced damage in human skin fibroblasts.
  - **Enzymes and peptides** from marine sources may act as anti-aging agents by protecting collagen stores.
- **Seagrasses**: *Zostera noltii* and *Z. marina* beach wrack contain **rosmarinic acid**, a phenolic compound with economic interest for cosmetic industries. *Cymodocea nodosa* detrital leaves contain high amounts of **chicoric acid**, a phenolic compound with therapeutic applications and high value in the nutraceutical market.

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Product Benefits, Formulations, and Real Example Products

- **Product Benefits and Formulations**
  - Marine-derived compounds provide active ingredients with **antioxidant, moisturizing, anti-inflammatory, and photoprotective properties** for creams and lotions.
  - They contribute to **anti-wrinkle and anti-aging effects**, often by protecting collagen.
  - Many marine skincare products on the market are not pure compounds but **treated extracts or enriched mixtures**.

- Examples of cosmeceuticals utilizing algal extracts include Biotherm®, La Mer®, Elemis®, OceanBasis®, Guam algae®, and La Prairie®. Microalgae extracts are found in Dermochlorella DG®, XCELL-30®, Alguronic Acid®, and Alguard®. Fungal extracts are used in Eyedeline and Brighlette by Lipotec.
- Marine polymers, such as SeaCode® from *Pseudoalteromonas sp.*, are used for soothing, reducing irritation, and providing hydrating and anti-wrinkle properties.
- Extremophilic marine microorganisms yield potent cosmetic ingredients like Hyadisine®, Antarticine®, and Hyafini®.

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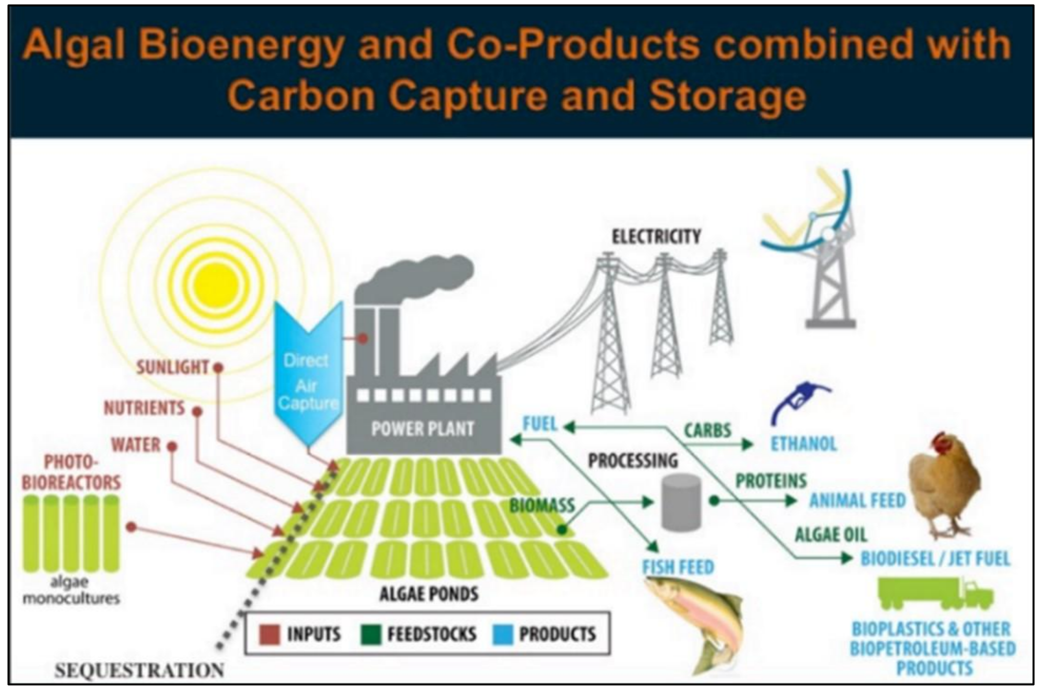
Biofuels and Energy

Sources of Biofuels and Energy Carriers from Marine Organisms:

- **Algae (Macroalgae and Microalgae):** These are particularly promising due to their ability to generate significant numbers of bioactive molecules and their high productivity.
  - **Microalgae** are considered important producers of highly bioactive compounds and can improve the nutritional profile of food due to their richness in polyunsaturated fatty acids (PUFAs) and pigments. They are a promising source for biofuels due to their chemical composition and global abundance, with some species capable of producing significantly more energy per tonne than conventional crops. They can grow in photobioreactors or open ponds, exploiting solar energy and greenhouse gases, which also helps mitigate air pollution.
  - **Macroalgae (seaweeds)** can be converted into energy carriers like methane (biogas) or bioethanol through fermentation. They also offer the advantage of not competing with food crops for land or freshwater resources. Invasive species like *Fucus* and *Sargassum* can be valorized for energy.
- **Thraustochytrids:** These oleaginous microorganisms are an increasingly important marine source of PUFAs, primarily DHA, and also potentially squalene and carotenoids, which are commercially important compounds with increasing market potential. They are also known to produce saturated fatty acids, serving as renewable sources for biofuels like biodiesel.
- **Marine Microorganisms (Bacteria, Fungi, Cyanobacteria):** Cyanobacteria, like *Arthrospira* (Spirulina), have potential for biohydrogen production. Marine bacteria have been explored for producing biofuels like bioethanol.



Source: Modified for educational purposes by C.H. Greene from original figure produced by Cellana, LLC. Accessed through EESI

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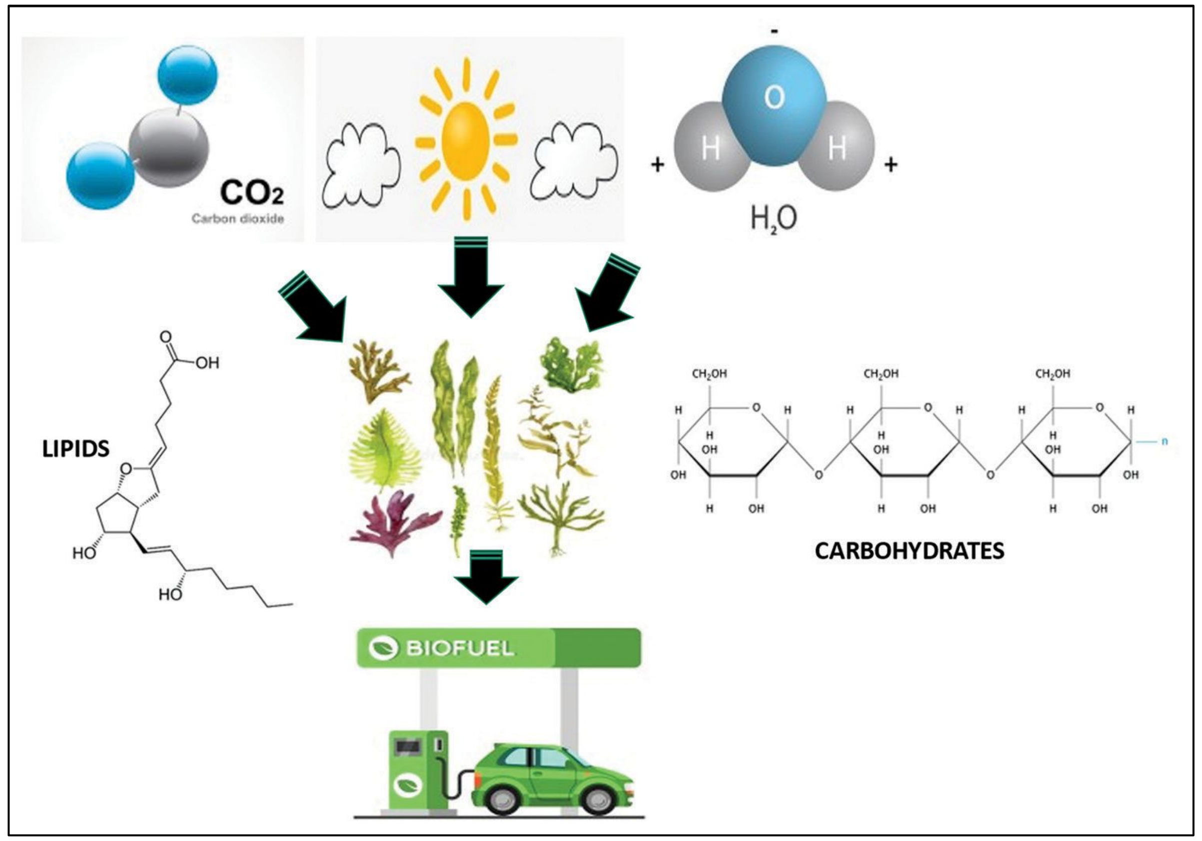
Biofuels and Energy



(Source: Olanrewaju, et. Al. 2024)

Types of Biofuels and Energy Applications:

- **Biodiesel:** Microalgae, with their high lipid content, are widely evaluated for biodiesel production. Efforts include optimizing growth conditions and genetic modification of species like *Nannochloropsis* and *Phaeodactylum tricornutum*.
- **Bioethanol:** Macroalgae and microalgae can be fermented to produce bioethanol. The use of residual and overabundant marine biomass for bioethanol and biogas production is encouraged to avoid competition with the biopolymers industry.
- **Biogas (Methane):** Seaweeds can be fermented into methane. The simultaneous production of combustible biomethane and disposal of undesirable marine biomass is a synergistic waste management concept with environmental benefits.
- **Biohydrogen:** Basic research is developing the direct production of hydrogen (H2) by marine microorganisms.
- **Other Energy Systems:** Seaweed can be used in renewable energy systems as an alternative to solid electrolytes in dye-sensitized photovoltaic cells, providing low-cost and environmentally friendly alternatives to expensive metal complexes.

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Biofuels and Energy

Production Technologies and Processes:

- **Cell Factories:** Cultivation of marine organisms in "cell factories" (macroalgae, microalgae, diatoms, cyanobacteria) can be done in open systems (ponds) or closed/artificial systems (bioreactors).
    - **Open Ponds:** Offer lower costs and high production capacity, using solar energy for biomass production. *Dunaliella salina* for β-carotene is an example of a successful open pond cultivation.
    - **Photobioreactors (PBRs):** Provide better control of growth parameters (nutrients, temperature, pH, CO2, O2), prevent contamination, and allow higher cell concentration and volumetric productivities. They come in various designs (flat, tubular, helical). While offering higher productivity, they are generally more expensive and energy-intensive than open systems.
- **Stress Cultivation (Milking Process):** Techniques like stress cultivation aim to increase the production of secondary metabolites by continuously removing them while keeping the culture active.
- **Heterotrophic and Mixotrophic Cultivation:** Some algae and cyanobacteria strains can grow heterotrophically in fermenters using carbon sources like glucose, which can be less costly and more controlled than photoautotrophic cultivation.
- **Extraction Technologies:** Clean processes like water extraction, supercritical fluid extraction (SFE), and subcritical water extraction (SWE) are researched to extract functional ingredients like lipids and phenols. SFE using carbon dioxide is considered a green, non-toxic, cheap, and non-flammable method for omega-3 fatty acid processing.
- **Biorefinery Concept:** This approach integrates biomass conversion processes to produce value-added chemicals, fuels, power, and heat from various types of side stream (waste) biomass. Marine biorefinery aims to produce higher-value biologically active ingredients from marine waste biomaterials. The cascade approach exploits all bioactive compounds, with biological leftovers valorized as feed or for bioenergy.
- **Enzymatic Processes:** Marine enzymes are crucial for biorefinery value chains, particularly in pre-treatment of biomass. They can facilitate the conversion of feedstock oils into biodiesel, and improve extraction efficiency of specific bioactive compounds from seaweeds.

Advantages of Marine Biofuels:

- **High Productivity:** Microalgae have a potential productivity tenfold greater than agricultural crops.
- **Non-Arable Land Use:** Production can take place on non-arable land, avoiding competition with food production.
- **Waste Utilization:** Algae can utilize wastewater as a nutrient source and/or

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Industrial Enzyme

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- **Marine Microorganisms:** Bacteria, fungi, and archaea are invaluable sources due to their adaptability to extreme conditions and their ability to produce a plethora of secondary metabolites and enzymes. Over 120 genomes of hyperthermophilic archaea, for example, have been sequenced, revealing interesting strains like *Pyrococcus*, *Thermococcus*, and *Thermotoga* that produce robust extremozymes. Marine fungi, in particular, are prolific producers of diverse enzymes, accounting for a significant percentage of newly described natural products.
- **Algae (Macroalgae and Microalgae):** While known more for biofuels, these organisms also contain enzymes, and processes involving their biomass often utilize enzymes for breakdown and conversion.
- **Thraustochytrids:** These oleaginous microorganisms are recognized for novel extracellular lipases and other hydrolytic enzymes like agarases, amylases, pectinases, chitinases, and carrageenases, suitable for diverse industrial applications.
- **Marine Invertebrates:** Enzymes are also extracted from marine invertebrates, though much research focuses on associated microorganisms.

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Industrial Applications of Marine Enzymes

- **Biorefinery Value-Chain:** This is a crucial area, where marine enzymes are used in the **pre-treatment of biomass** (e.g., from aquaculture like algae and seaweeds) to produce renewable carbon-based raw materials, and also to manipulate feedstock oils for **biodiesel production**.
  - Examples include **cellulases** and other **carbohydrate-active enzymes** (like hemicellulases, pectinases, proteases, and amylases) from marine microbes, which are explored for saccharification of seaweed biomass. **Lipases** are widely evaluated for converting various feedstock oils into biodiesel.
  - Waste streams from squid manufacturing or mussel processing can be valorized by enzymatic hydrolysis to produce nutrient supplements for bacterial cultivation, or for bioethanol and biogas production.
- **Food Industry:** Marine enzymes are used in food processing, offering advantages over traditional enzymes due to their activity under unusual conditions.
  - They are utilized for the production of **functional ingredients** like peptides with antihypertensive and immunomodulatory properties from fish proteins.
  - **Cold-active enzymes** are particularly useful in the food and beverage industries for processing heat-sensitive products, preserving their nutritional and organoleptic qualities.
  - Enzymatic approaches are also explored for **deodorization of fish oil** and for **chitin and chitosan production** from shellfish waste.

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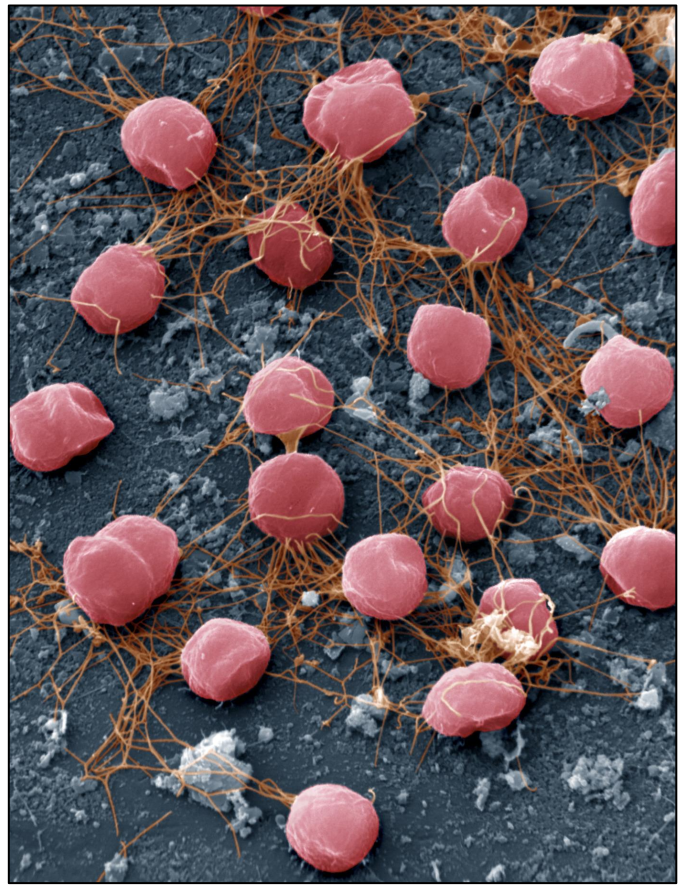
Industrial Applications of Marine Enzymes

- **Fine Chemistry and Laboratory Techniques:** Marine enzymes enable **selective and efficient extraction or modification** of complex marine molecules, contributing to sustainable processes in fine chemistry.
  - They are used for the **synthesis of novel products** and for **improving extraction efficiency** of specific bioactive compounds from seaweeds.
  - Specific examples include the production of **glucose from sea lettuce** using sea hare enzymes, and the asymmetric synthesis of D-methyl lactate by a marine microbial esterase.
  - **Pfu polymerase** from *Pyrococcus furiosus*, an extremophilic marine microorganism, is a well-known example used in PCR for high replication fidelity in laboratory applications.
- **Bioremediation and Environmental Applications:** Marine enzymes play a significant role in **bioremediation** by transforming toxic substances into less hazardous compounds, integrating them into biogeochemical cycles.
  - Microorganisms synthesize enzymes that can **degrade plastics** (lipases, alkane hydroxylases, laccases) and are involved in the **decolorization of industrial effluents**.
  - Marine fungi and their laccases are specifically used in the textile industry to treat salty effluents.
  - **Carbonic anhydrases** from marine extremophiles are being investigated for **CO2 sequestration** and as **biomarkers** for environmental monitoring.

Pyrococcus furiosus



(Source: Kengen S.W.M. 2017)

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Production Technology of Marine Enzymes

- **Cell Factories & Bioreactors:** Cultivation of marine organisms in "cell factories" (macroalgae, microalgae, bacteria, fungi) occurs in open ponds or controlled **photobioreactors (PBRs)** and fermenters. While PBRs offer better control over growth parameters and higher volumetric productivities, they are generally more expensive and energy-intensive.
- **Metagenomics:** This genetic approach allows the study of complex microbial mixtures from marine environments, identifying genes involved in bioactive compound biosynthesis, leading to the **discovery of novel enzymes** even from unculturable microorganisms. The INMARE project, for example, generated a large genomic and metagenomic collection of enzymes for industrial operations.
- **Genetic and Metabolic Engineering:** Techniques like recombinant DNA technologies and metabolic engineering are used to **increase the productivity** of an organism or improve the yield and characteristics of a product by optimizing metabolic pathways and expressing enzymes in suitable hosts.
- **Bio-processing Technologies: Enzyme-mediated hydrolysis** is a key bio-processing technology that adds value to marine by-products. Methods like **membrane bioreactors** equipped with ultrafiltration membranes are used for efficient recovery of functional ingredients.
- **Extraction Technologies:** New and environmentally clean technologies, such as **supercritical fluid extraction (SFE)** and **subcritical water extraction (SWE)**, are researched to extract functional ingredients, including enzymes, using non-toxic solvents. **Enzyme-assisted extraction (EAE)** methods are being developed to increase efficiency and reduce extraction time. The **"milking process"** is a non-destructive regenerative extraction technique that allows continuous removal of metabolites while keeping the culture active, reducing costs associated with harvesting and cell disruption.

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Bioremediation

Pollutant Degradation

- **Hydrocarbons and Aromatics:** Marine bacteria from phyla like Proteobacteria, Actinobacteria, Cyanobacteria, Bacteroidetes, and Firmicutes are used for degrading aromatic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), in oil-polluted sediments and petroleum spills. Specific hydrocarbon-degrading bacterial taxa have been found on plastic marine debris, suggesting their potential in plastic degradation.
- **Plastics:** Microorganisms synthesize enzymes like **lipases, alkane hydroxylases, and laccases** that can degrade plastics.
- **Industrial Effluents:** Marine fungi producing lignin-degrading enzymes are used for **decolorization of highly colored effluents** from paper, pulp mills, textile, and dye-making industries. These fungi also demonstrate strong oil degradative capabilities.
- **Salty Effluents:** Marine fungi and their laccases are specifically used in the textile industry to treat salty effluents.
- **Other Pollutants:** Microalgae have shown potential in degrading emerging contaminants like pharmaceuticals and personal care products.
- **Mechanisms:** The metabolic ability of naturally occurring organisms allows them to transform toxic substances into less hazardous compounds. Studies have explored anaerobic degradation of complex hydrocarbons by marine sedimentary bacterial communities and the enzymatic reduction of chromate by sulfate-reducing bacteria.

Heavy Metal Removal

- **Bioaccumulation:** Both microalgae and macroalgae can **bioaccumulate heavy metals** such as arsenic, cadmium, mercury, and lead, removing them from surrounding waters.
- **Microalgae Species:** Genera like *Chlorella*, *Scenedesmus*, *Tetraselmis*, and *Arthrospira* are reported for their high uptake capacity of toxic heavy metals.
- **Mechanisms:** Microalgae remove heavy metals through both **adsorption** (rapid surface adsorption by cell wall polysaccharides and functional groups) and **absorption** (a slower, energy-requiring process into the cell interior). They also synthesize metal-binding peptides, such as cysteine-rich metallothionein, to neutralize toxic effects.

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Bioremediation

Nutrient Removal and Waste Treatment

- **Wastewater Treatment:** Microalgae, seaweeds, and mussels can remove nutrients from industrial and aquaculture wastewaters. For example, the cultivation of microalgae on diluted pig manure can be used for electricity production or as feed.
- **Biofilters:** Mussels act as natural filters for extracting microalgae from seawater used as cooling water or near fish farms. Biofilms are also used as **biofilters in recirculating aquaculture systems** to convert ammonia to nitrates, restoring healthy conditions for farmed fish and shrimp.
- **Valorization of By-products:** Waste streams from seafood processing (e.g., squid manufacturing, mussel processing) can be valorized by enzymatic hydrolysis to produce nutrient supplements for bacterial cultivation, or for bioethanol and biogas production.

Climate Change Mitigation

- **Carbon Capture:** Micro- and macroalgae contribute significantly to **carbon capture** by sequestering carbon from the atmosphere, with a substantial part of macroalgal biomass being transported to deep sea and sediments for long-term sequestration.
- **Carbonic Anhydrases:** Enzymes from marine extremophiles, such as carbonic anhydrases, are investigated for **CO2 sequestration** due to their role in biomimetic CO2 capture.
- **Methane Emission Reduction:** Adding marine red seaweed *Asparagopsis taxiformis* as a feed amendment to livestock has been shown to reduce enteric methane emissions by up to 98%.

Antifouling: Marine organisms and their compounds, particularly from sponges and certain bacteria, are explored for their antifouling activities to prevent biofouling on marine surfaces.

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Environmental Monitoring

Marine biotechnology also contributes to environmental monitoring through the use of **biomarkers** and **biosensors**:

- **Bioindicators:** Marine organisms like mussels (*Mytilus edulis*) are used as **bioindicators** to monitor heavy metal pollution and assess exposure to environmental pollutants.
- **Enzymatic Biomarkers:**
  - **Biotransformation Enzymes:** Studies investigate biotransformation enzymes (phase I and II) and stress proteins (e.g., heat shock protein-70) as biomarkers. For instance, patterns of MAPK phosphorylation in mussels can indicate exposure to different pollutants.
  - **Antioxidant Enzymes:** Changes in antioxidant enzyme activities (e.g., catalase, superoxide dismutase, glutathione peroxidase) in organisms like mussels and fish are assessed as responses to petrochemical contamination or metal exposure.
  - **Carbonic Anhydrases:** These metallo-enzymes are also discussed for their potential as novel biomarkers in environmental monitoring and the development of biosensors for metals.
- **Transcriptomic Studies:** Transcriptomic differences in fish liver exposed to flame retardants are investigated to assess molecular responses to pollution.
- **Bioinformatic Studies:** Bioinformatic approaches are used to study the effect of metal pollution on enzymes of seawater organisms, providing insights into physiological roles.
- **Biosensors:** Marine biotechnology supports the development of biosensors to measure changes in environmental conditions, including biological and microbial ecosystems.

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Cosmetics: Anti-aging and Skin Care Products
Example: ALGOTHERM (France) – Blue Biotechnology

- **Source**: Marine algae and seaweeds
- **Product**: Anti-aging creams and serums enriched with marine collagen and polysaccharides
- **Value Addition**: Marine-based actives provide natural antioxidants and hydration with sustainable harvesting methods. These products cater to the growing demand for natural, effective, and eco-conscious skincare solutions.

Functional Foods and Nutraceuticals
Example: Astaxanthin from *Haematococcus pluvialis* or marine microalgae

- **Source**: Cultivated marine microalgae
- **Product**: Nutritional supplements with antioxidant and anti-inflammatory properties
- **Value Addition**: Natural marine-derived compounds with high health value, marketed for cardiovascular and immune system support.

Pharmaceuticals: Antiviral and Analgesic Agents
Example: Ziconotide (Prialt®) by Elan Pharmaceuticals

- **Source**: Cone snail venom (*Conus magus*)
- **Product**: A non-opioid analgesic for severe chronic pain
- **Value Addition**: Offers an alternative to traditional opioids, with high specificity and reduced risk of addiction, showcasing marine organisms as sources of novel drug compounds.

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Biomedical Materials: Collagen and Chitosan
Example: Marine-derived wound dressings
- **Source**: Fish skin, jellyfish, and crustacean shells
- **Product**: Biocompatible wound healing materials and scaffolds for tissue engineering
- **Value Addition**: Marine collagen and chitosan are biodegradable, promote healing, and serve as sustainable alternatives to synthetic biomaterials.

Food Industry: Marine Enzymes for Processing
Example: Proteases and lipases from deep-sea bacteria
- **Source**: Marine microorganisms
- **Product**: Used in the hydrolysis of proteins in food processing (e.g., fish sauce, dairy)
- **Value Addition**: Enhanced efficiency under extreme processing conditions (temperature, salinity, pH), offering cost-effective and sustainable alternatives to chemical processes.

Industrial Biotechnology: Bioplastics and Biofuels
Example: Production of PHA (polyhydroxyalkanoates) by marine bacteria
- **Source**: Marine microorganisms
- **Product**: Biodegradable plastics
- **Value Addition**: Environmentally friendly alternatives to petroleum-based plastics, with potential for scaling using marine biomass or by-products.

- **Example**: *Biomaterials from Chitosan* developed by Indonesian researchers (e.g., IPB University, UI)
- **Source**: Shrimp and crab shells (by-products of seafood industry)
- **Product**: Chitosan-based wound dressings, drug delivery films, and antimicrobial coatings
- **Value Addition**: Converts waste from marine food processing into high-value biomedical products with applications in clinics and hospitals.

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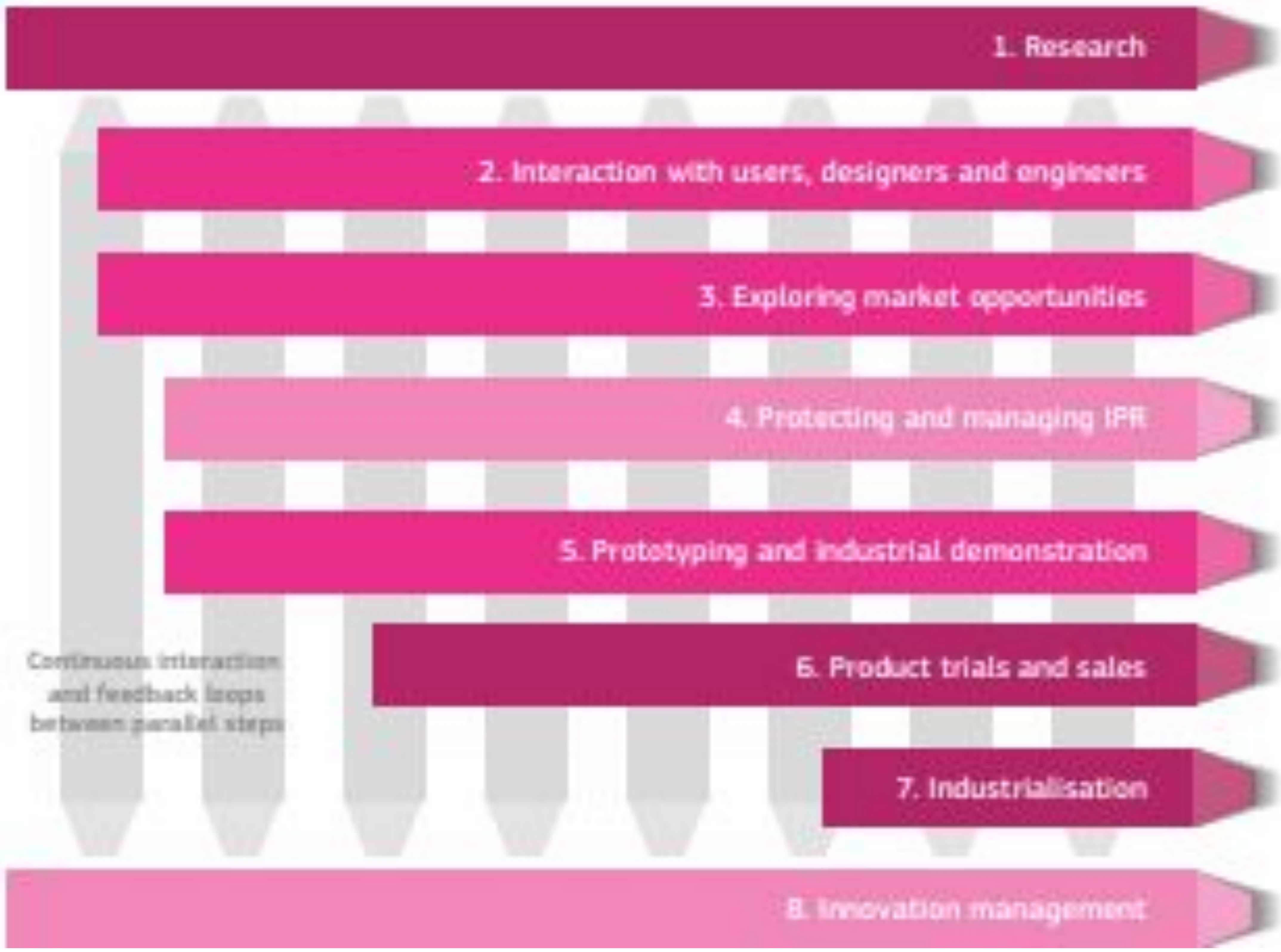
Translational Research



(Source: EU, 2013)

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Project: 101129136 — SustainaBlue — ERASMUS-EDU-2023-CBHE