



Review article

Seaweed farming: A perspectives of genetic engineering and nano-technology application

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ARTICLE INFO

Keywords:

Seaweed

Cultivation

Nanoparticles

Genetic engineering

ABSTRACT

In order to meet the growing demand for resources, there is a rising interest in macroalgae cultivation worldwide due to their potential as a source of food, fuel, and bio-products. However, large-scale and sustainable seaweed cultivation has been a persistent challenge. Specific fundamental issues need to be addressed to maximize the benefits of seaweed production. This article reviews a plan for transitioning to an environmentally sustainable aquaculture system incorporating non-toxic nanoparticles. It also provides an overview of genetic enhancement techniques for macroalgae species to realize their potential fully. Additionally, the article discusses the need for advanced tools and concepts to overcome the challenges in seaweed identification and cultivation and emphasizes the importance of a coordinated effort in fundamental and applied research using emerging technologies to ensure long-term practicality.

1. Introduction

Seaweeds or macroalgae are multicellular photosynthetic organisms that can float freely or be attached to objects like rocks in the subtidal or intertidal part of the marine environment [1]. The production of seaweed has increased significantly over the past few decades. It is predicted that just 2% of the ocean's surface might be used to cultivate seaweed species, increasing current agricultural food production twofold [2]. Growing seaweed has received a lot of interest as a sustainable source of bioenergy feedstock as it is more productive ($1600 \text{ g C m}^{-2} \text{ year}^{-1}$) than terrestrial plants ($470 \text{ g C m}^{-2} \text{ year}^{-1}$) [3]. It now accounts for 51.3% (34.7 MMT, wet weight) of all marine aquaculture worldwide, with China and eight other Asian nations dominating output (99.6%) [4,5] (see Figs. 1–6).

According to ([8], seaweed farming can accomplish various objectives while advancing several of the Sustainable Development Goals set forth by the United Nations (UN SDGs). These include eradicating hunger (SDG2), promoting health and well-being (SDG3), ensuring access to affordable and clean energy (SDG7), addressing climate change (SDG13), and preserving life in the oceans (SDG14), all of which have resounding advantages that support other SDGs [8]. In coastal countries, seaweed farming is a popular method for developing a sustainable blue economy [9]. Seaweed can also enhance the worldwide vegetable diet consumption and food supply chain.

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<https://doi.org/10.1016/j.heliyon.2023.e15168>

Received 6 August 2022; Received in revised form 1 March 2023; Accepted 28 March 2023

Available online 7 April 2023

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Seaweed can be grown offshore, on land, and in integrated aquaculture systems. According to the species, location of the farm, and growing facilities, seaweed is chosen for cultivation. In Integrated multi-trophic aquaculture (IMTA), feed species are combined with extractive species, which thrive by consuming organic and inorganic waste from aquaculture. IMTA systems can be modified depending on the physical, chemical, environmental, biological, sociological, and economic factors unique to different world regions. IMTA can support sustainable aquaculture, which has advantages for the environment, the economy, and society. This can be accomplished through product variety and potential value payments. Higher financial benefits are brought on by increased production efficiency and nutrient recycling [10]; Osch et al., 2019).

Seaweed farming is based primarily on conventional methods, in which seaweeds are sensitive to diseases and environmental issues. Most seaweeds are grown from seedlings derived from cultivated germplasm via vegetative propagation to boost productivity. There is increasing attention among various stakeholders to engage in producing different macroalgae species broadly. Expansion of seaweed cultivation requires new associates and the enhancement of existing ones. A synergy between various growth parameters is necessary to ensure optimal seaweed yield from the cultivation systems.

Logistical issues for traditional seaweed growers include locating suitable agricultural sites, infection, and seed mortality brought on by extreme weather and polluted water environment. Increasing the efficiency of seaweed cultivation requires new technology and the enhancement of existing ones. Nanotechnology and Modern biotechnology can be regarded as one of the finest choices for increasing production by overcoming various issues.

The utilization of high-tech cultivation methods, such as smart engineering and genetic engineering techniques, offer promising opportunities for the commercial development of marine algae. By introducing modified morphological traits, enhanced characteristics, and improved growth rates, seaweed production capacity can be significantly expanded. For instance, researchers can use genome editing techniques to understand better the relationship between genotype and phenotype and gene transformation techniques and approaches to identify promoter sequences. In addition, synthetic biology tools, such as de novo genome design, can create new systems from individual modules [11].

This review considers various technical aspects of nanotechnology and genetic engineering strategies to enhance the macroalgae farming technique. Hence, the study focuses on the following objective.

- To investigate the various innovative technologies in aquaculture, including nanotechnology and genetic engineering.
- To discuss the prospects of remote sensing and advanced computational tools in seaweed farming.
- To provide some recommendations and future directions for advanced seaweed farming techniques.

2. Application of nanotechnology

Nanotechnology is the study, advancement, synthesis, modification, and use of functional material devices and systems by controlling matter at the nanometre scale (1–100 nm, where 1 nm is equal to 10^{-9} of a meter), that is, at the atomic and molecular levels. Nanotechnology is quickly gaining traction as the scientific and technological foundation for the next generation of new advances. Many nanomaterials have been produced and applied to various research disciplines. Nanotechnology has also considerably boosted specialized activity in a variety of industrial applications. In aquaculture, there are several nanomaterials applications, including pond

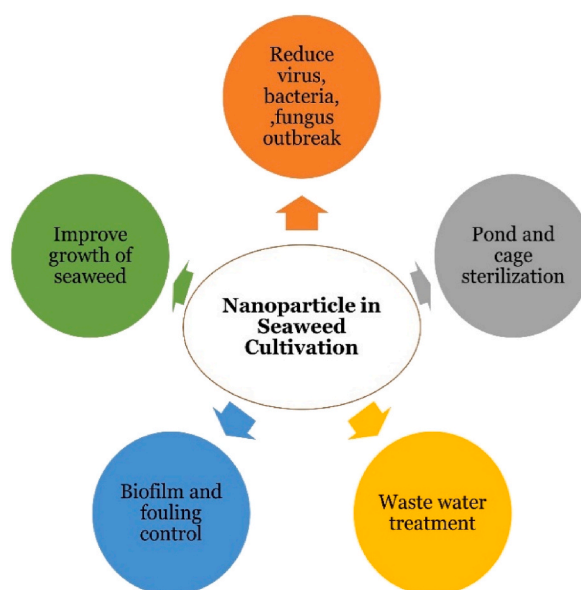


Fig. 1. Application of nanoparticles.

sanitation, water purification, control of marine pathogens, and effective delivery of nutrients and medications [12]; S [13]. Nanotechnology is considered a prolific road for addressing significant problems of seaweed farming, such as monitoring diseases and parasites multiplying, biofouling control, and the potential to improve aquaculture productivity. For instance, nanoparticles substantially impact the financial feasibility of microalgae-based products [14–16]; hence nanomaterial's ability promotes a new green movement with fewer threats for farmers also [17] reported that Ni–Cu/TiO₂/Ti electrode is a promising candidate for a nanostructure sensor of glucose concentrations detected in polluted and unpolluted growth conditions of *U. lactuca*. Nanosensor devices can also detect low quantities of parasites, bacteria, and viruses in the water and polluting components. This is especially essential in commercial aquaculture outbreaks because it might take a long time for the etiological agent to produce an impact and be diagnosed, delaying pathogen control treatment and causing significant economic losses. In this context, nanotechnology can solve this problem in macroalgae farming by detecting and eradicating viruses early on.

An extensive literature frame provides a concise description of nanotechnology's applications in aquaculture; however, there is little evidence of the use of nanoparticles in seaweed production. This technology may provide innovative and economic development routes to improve seaweed cultivation in the long term. Without question, new and inventive approaches are critical to macroalgae cultivation's long-term success. Finally, we emphasized that the aquaculture industry's embrace of nanomaterials and nanotechnology will be slow. Many possibilities, however, point to a potential approach to tackling macroalgae cultivation's major issues shortly. Overall, incorporating nanotechnology into various aquaculture techniques appears to be unavoidable and will undoubtedly lead to further advancements in the future. Below are the different foreseeable roles of nanoparticles in terms of their applications in seaweed cultivation (Fig. 1).

2.1. Few works of nanotechnology on seaweed cultivation

With fewer farming risks, the potential of nanomaterials inspires a new green revolution. Finally, we stressed that adopting nanomaterials and nano-technology in aquaculture will be a gradual process. To address the increasing challenges of sustainable production and food security in the upcoming years, nano-technology will have several applications in seaweed growth. However, there is still a long way to go. Although it is difficult to predict how a nanodevice would function in seaweed, we must begin with actual field tests to address some of the issues raised. The use of nanomaterials in the growing and harvesting of seaweeds is becoming more and more critical, but the field is still young and needs space for both their practical application and the prevention of adverse side effects. Precautions must be taken due to the impact of various nanoparticles and how they interact with multiple seaweeds in changing environmental circumstances. According to Ref. [18] in terms of recycling and NM functionalization with biocompatible elements, magnetic nanoparticles may help lower the toxicity, This could aid in the cost-effective, large-scale production of seaweeds that is also environmentally beneficial. Magnetic nanoparticles increased dispersibility to reach significant harvesting capacity; yet, their oxides were difficult to recycle or reuse. Cubic spinel ferrites coupled Mn, Cu, and Zn divalent ions revealed strong chemical stability, excellent biocompatibility, and inexpensive production costs aside from magnetic nanoparticles [19,20]. Furthermore, the diversification of macroalgae farming could be aided by manufacturing a wide range of high-value-added goods. In addition, the process's techno-economic evaluation would help with operational improvement to achieve overall energy-efficient harvesting and production of seaweed. Table 1 provides the summary of selected works on Nano-technology use in Seaweed farming

2.2. Adverse effect of nanoparticles

It has been revealed that components based on nanotechnology are destructive to the environment and human health. As a result, it's crucial to consider the damaging effects of nanomaterials on aquatic ecosystems and human health.

1. Nanoparticles negatively affect DNA replication as a result of assimilation, which could result in genetic changes [21].
- 2 [22] demonstrated that nAl₂O₃ inhibited *Dunaliella salina* growth indicating a link between NP concentration. Furthermore, the rise in NP content was accompanied by a decrease in chlorophyll and carotenoid levels in microalgae.
3. At low concentrations, ZnO nanoparticles are highly cytotoxic and have a high capacity for protein adsorption [23].
4. Water-soluble stable NPs can accumulate in the aquatic systems, and the activity of marine organisms is impacted by their exposure to the aquatic food chain in a concentration-dependent approach [24–26].

Table 1
nanoparticles application as emerging 'smart' technologies in aquaculture.

Nanoparticles	Applications	Reference
Nanodevice	Nanonets can improve water quality attributes by raising the pH of the water.	[52]
nCuO, nZnO, nSi	Promising contenders with a high specific surface area ratio provide a more effective defence against fouling agents.	[53]
AgNPs	Reduce fungus infection in rainbow trout fertilized ovules. In the future, it might be utilized to treat fungal diseases in seaweed.	[54]
AgNPs	Experiments show that bacteria cannot develop resistance to AgNPs to antibiotics	[55,56].
Fe ₂ O ₃ , zero-valent nano iron	Significantly increase in growth and biochemical composition with adequate dose of nano iron	[57].
Ag, Au NPs	The antimicrobiofilm activity against common marine biofilm-forming bacteria such as <i>A. hydrophila</i> , <i>Salmonella</i> sp., and <i>S. liquefaciens</i>	[58]

3. Biological engineering

3.1. Breeding to improve seaweed quality

Collecting seaweed strains with favourable environmental characteristics of high development rates, carrageenan content, disease tolerance, and rapid development is the foundation of a successful seaweed breeding program. Seaweed breeding techniques adapt to keep the farming sector growing in an ever-changing environment. Breeding seeks to alter a population's genetic makeup to enhance its characteristics according to its intended use. The first step in developing breeding is deciding on the attribute(s) to improve, such as the composition, characteristics, developmental factors, and modes of action to biotic and abiotic, which influence yield and productivity.

3.2. Selective breeding

Over ten years of study, a method for artificially producing sporelings from filamentous sporophytes was broadly applied. In Japan, by the 1960s [27], selective breeding with spores isolated from blades with good development was made possible. Parents with a larger ratio of beneficial alleles and a lower proportion of less acceptable alleles are identified in selection-based breeding procedures. Although selective breeding is used to generate superior variations, mostly limited to macroalgae genera like *Porphyra* (Rhodophyta) and *Laminaria* (Phaeophyceae). Since 1949, when *Porphyra*'s life cycle and reproduction control were discovered, only 30 cultivars have been created [28]. Several high-value seaweed genera, including *Saccharina* [29], *Undaria* (Phaeophyceae), and *Porphyra* (Rhodophyta) [30,31], successfully used selective breeding and genetic improvement of cultivars for improving output, flavor, and other factors. At the Hyogo Prefectural Fisheries, cultivar development via the selection of thalli generated from protoplasts of selected cultivars has undertaken to improve the effectiveness of selective breeding. This technology allows for the collection of a huge quantity of single cells at once, increasing the chances of detecting variations caused by mutations [32].

The 59 *Neopyropia yezoensis* (formerly *Porphyra yezoensis*) (Nori) (Rhodophyta) was studied for a selective breeding program of economically important nori crops using the ITS1 region. Selective breeding in Japan achieves most nori cultivar enhancement for aquaculture [33]. Eukaryo ABC (Algae Breeding Cultures) is a Norwegian organization that specializes in selective seaweed breeding to create cultivars or "varieties" with higher yields, better consistency, and stability than wild seaweed. In general, such breeding functions as an effective partnership with industry where progeny is produced for the sustainability of entire industries. A MARINER Category 5 project led by the Woods Hole Oceanographic Institution aims to create a selective breeding program for, *Saccharina latissima* (Phaeophyceae), one of the most economically significant kelp types. The project's objective is to boost seaweed farming's production and profitability. Selective breeding has not yet produced successful seaweeds from the agarophytes, carragenophytes, and green seaweeds groups. Selective breeding concept is presented in Fig. 2.

Recurrent self-hybridization and selection are used in linebreeding. Line-breeding is used by some plants and the few seaweed

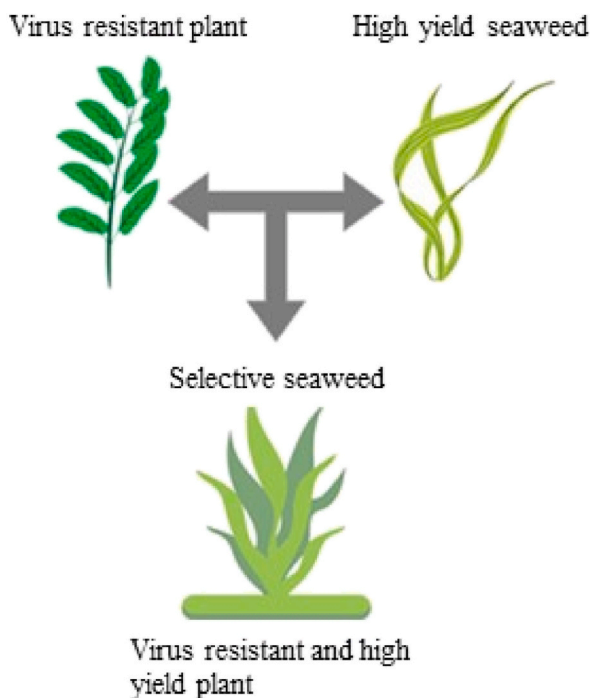


Fig. 2. Diagram showing selective breeding.

genetic enhancement projects that are currently underway. To establish lines and the superior crossbred or F1 individuals from those lines, trait selection is combined with inbreeding.

3.3. Gene modification through mutagenesis

Random mutagenesis generated by either a physical or a chemical mutagen is employed to cause genetic alterations in algae (Fig. 3).

Chemical mutagens are standard mutagenesis methods in a wide variety of organisms. It is the most common way to generate mutations in phenotypic traits. Mutagenic chemicals like N-methyl-N'-nitro-N-nitrosoguanidine and ethyl-methane sulfonate have been used in marine macroalgae. For example, EMS has been used to create mutants of the red seaweed *Gracilaria tikvahiae* [34], which exhibit varied increasing patterns and thallus thickness, probably due to variations in the size of the medullary and sub-cortical cells of thallus [35]. Still, there is a significant chance of contamination during sewage disposal, which is a huge downside.

Physical mutagens consist of several forms of radiation that fall into two groups. The first group includes X-rays and gamma rays, generally considered to travel in waves and are part of the electromagnetic spectrum. The second form of radiation is corpuscular radiation, which comprises moving particles such as protons, neutrons, and electrons [36]. Among those physical mutagens, gamma rays have been used intensively in mutation breeding research to improve crop species' agronomic characteristics and quality. Physical mutagens are more likely to produce chromosomal alterations and more prominent DNA. Irradiation used on the brown macroalgae *Ectocarpus siliculosus* (Phaeophyceae) and the green seaweed *Ulva compressa* (formerly *U. mutabilis*) (Chlorophyta) has proven to be safe and effective [37]. Despite advances in genomic studies in terrestrial plants, seaweeds have rarely been studied globally and are not included in approaches to unravel gene functions. As a result, long-term seaweed genetic improvement initiatives should be started and developed. These mutations were created at random and without being labeled, they can only be identified using forward genetic techniques and molecular instruments.

3.4. Protoplast fusion and somatic hybridization

An *in vitro* genetic modification approach is more successful than traditional strain enhancement strategies like mutation and selection. Using protoplasts from multiple sources takes advantage of natural genetic diversity and creates new genetic pairings that boost various functional features. This method has been widely used in terrestrial plants, resulting in several agricultural varieties with increased productivity or tolerance to biotic/abiotic. Bicolor, red and green chimera seedlings result from the protoplast fusion between two *Gracilaria* species, namely *G. tikvahiae* (green pigmented) and *G. chilensis* (red pigmented) [38]. Researchers generated seaweed variations with superior agronomic qualities via protoplast fusion between *Gayralia oxysperma* (formerly *Monostroma oxyspermum*) and *Ulva reticulata* (Chlorophyta) [39]. Fig. 4 illustrates the gene modification approach through regeneration

Utilizing the inherent genetic variety of phylogenetically distant species, somatic hybridization by protoplast fusion is a practical method that promotes the recombination of economically significant features [40]. For the first time [41], demonstrated successful *trans*-divisional protoplast fusion and regeneration in *Monostroma* and *Porphyra* somatic hybrids [42,43] discovered protoplast-based methods for generating seedling stocks (micro thalli) that can survive in an incubator for several years while still having the ability to grow into *Ulva* and *Monostroma* leafy thalli. Although protoplast synthesis and regeneration are not financially viable, *Porphyra*,

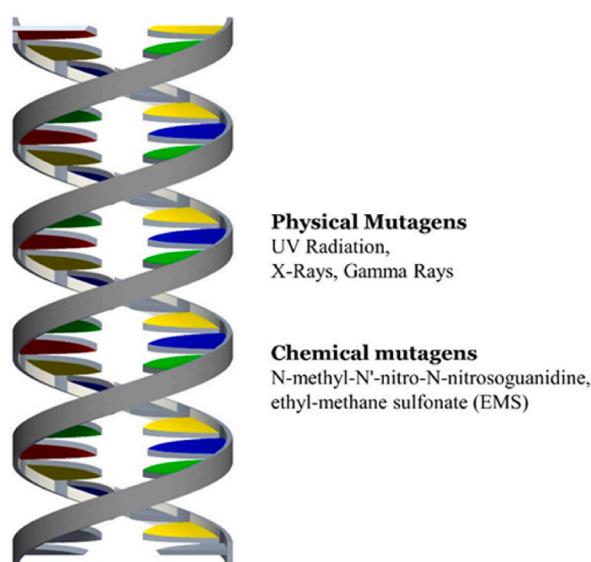


Fig. 3. DNA mutation by physical and chemical mutagen.

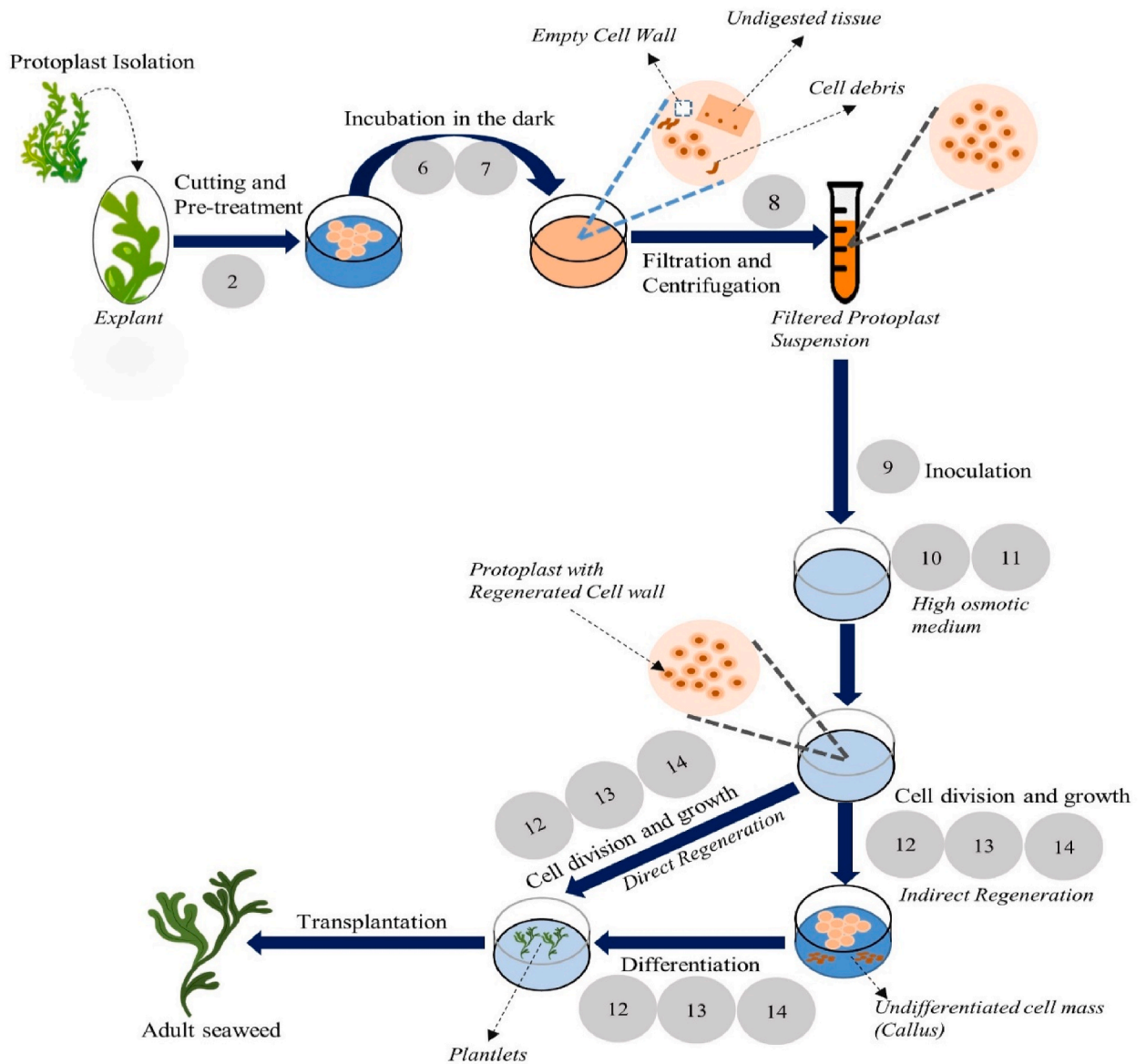


Fig. 4. Macroalgae separation, cultivation, and regeneration [6].

Laminaria, *Undaria*, and *Gracilaria* are a few species of seaweed that are ubiquitous adopting the procedure [44]. Despite significant protoplast separation and regeneration achievements in various seaweed species, seaweed research lags significantly behind terrestrial plants.

3.5. Genetic transformation

In contrast to agricultural plants, macroalgae genetic transformation processes are still in the early phases of development. Under the direction of the genes delivered into cells, transformations can be classified as genetic (stable) or temporary (transient). In contrast to transient transformation, where introduced foreign genes are typically lost quickly, genetic recombination preserves genes in the genome over generations of cells.

Since the early 1990s, researchers have worked hard to find approaches to genetic transformation in seaweeds to create new strains with beneficial traits for business and medicine. But because it's a laborious process, most early studies were disclosed in conference abstracts rather than full publications. This condition has impeded scientists' ability to learn about gene activities in many physiological processes and the use of seaweeds in biotechnological applications. Creating an effective transformation process and selecting appropriate reporter genes and promoters are the foundations for building a seaweed transformation system [45]. To use these regulatory domains as prospective algal promoters for efficient and steady expression of foreign genes, considerable work was done to

understand the gene regulatory domains in the algal system. Therefore, choosing influential endogenous promoters is essential for limiting the high expression of alien genes as promoter determines how well foreign genes are expressed in transformants, which is critical for genetic engineering. The NOS (nopaline synthase) promoter from *Agrobacterium tumefaciens* T-DNA and the 35S cauliflower mosaic virus (CaMV) are the two most common used promoters for constitutive expression [46]. used a fragment of 18SrDNA in a vector pQD-GUS for the first time to use homologous promoters for foreign gene expression in *Porphyra* protoplasts, comparing GUS protein expression to that of the original pBS-GUS vector. Another study using the SV40 promoter (from the simian virus) found that the lacZ reporter gene was expressed uniformly in regenerated *Laminaria* sporophytes, demonstrating a high transcription recognition efficiency regardless of tissue specificity [47]. Functionality of the Cauliflower Mosaic Virus 35S promoter in *Chondrus* which has also worked well in, *Gracilaria changii* [48], *Kappaphycus alvarezii* [49] and *Wildemanina miniata* (formerly *Porphyra miniata*) (Rhodophyta) [50] (

Additionally, the selection of beneficial transformants can be sped up by using the right reporter genes. Macroalgae have previously been utilized as reporters for the bacterial -galactosidase lacZ and -glucuronidase (GUS) genes. According to Ref. [51], fluorescent proteins can be expressed briefly in *Neopyropia yezeensis* (Rhodophyta) gametophytic cells. This raises the possibility of using fluorescent proteins as reporter genes in upcoming genetic transformation studies. Particle bombardment, particle guns, or biolistics is one of the most common methods for achieving nuclear and organelle transformation in organisms for algae and plants, fungi, insects, animals, and even bacteria. Below are different methods applied to seaweed for genetic transformation, as shown in Table 2.

Although genetic transformation techniques are positively practical to several microalgae, very little research on seaweed has been published because microalgae genomic information is abundant and comprehensive, whereas seaweed genomic information is limited. Seaweed molecular biological studies are now proceeding more slowly than land green plant molecular biological studies due to challenges with efficient genetic transformation methods. A genetic transformation system's development would improve genetic engineering and our biological knowledge (Fig. 5).

3.6. Less acceptability of genetically modified algae

Genetic engineering has the potential to address several of these tech issues and environmental concerns, but still, there is less acceptability of genetically modified algae. GE algal research is only permitted in accredited labs and pilot plants in the EU. Safety procedures must be taken to prevent any hazards that may ultimately arise from the uncontrolled release of these GE algae into the environment. The legal status of GE algae (and genetically engineered organisms in general) in the United States was reviewed in 2014. The authors concentrate on the difficulties in controlling modified microorganisms, one of which is the research and development phase, where it's possible that the risks of application won't be understood until the research is over [63]. Recent instances of approved outdoor GE algae growing at facilities run by Sapphire Energy in California, United States, and StelaGenomics México in Guanajuato, Mexico. Maintaining secondary containment, netting, and checking bucket traps outside the main growing pond for the development of the GE algae were among the TERA's requirements for Sapphire Energy [64] under the Biosafety Law of GMOs, Mexico made similar demands [65]. According to Ref. [66], there is no proof of doubts or even resistance to the GE algae. This can be due to the lack of coverage in the media and the limited public awareness of GE algae.

A coordinated effort in fundamental research is urgently needed to assess genetic resources and develop adequate genetic conservation policies, which are, to date, almost totally absent, to ensure the sustainability of GE algal cultivation and its public acceptance as an environmentally sustainable activity. The federal government of a country must be notified and, in some situations, approved using genetically modified algae in contained or uncontained applications. Most nations have specific legislation for actions involving altered microorganisms that apply to algae. According to a US Environmental Protection Agency (EPA) judgment (TSCA), any altered algal biomass is governed by the Toxic Substances Control Act. Before using the modified algae for commercial purposes, importing it, or conducting outside research and development (R&D), the authorities must be notified. The final biosafety evaluation of a genetically modified seaweed requires interdisciplinary research on algal genetics, physiology, reproductive biology, and ecology from the molecular to at least the local aquatic ecosystem level through mathematics, biology, chemistry, physics, and even sociology when taking into account environmental issues. These developments will open up countless opportunities for seaweed genetic

Table 2
Seaweeds that were genetically transformed.

Method	Technique	Seaweed	Promoters	Marker	Reference
Electroporation	Electrodes create voltage imbalance across the cell membrane, enabling substances to travel through the phospholipid bilayer into the cell.	<i>Neopyropia yezeensis</i> (formerly <i>Porphyra yezeensis</i>), (Rhodophyta)	CaMV 35S	GUS	[46].
Microparticle Bombardment	Target cells collide with accelerated DNA-coated non-reactive metal (gold or tungsten) micro projectiles	<i>Gracilaria changii</i> (Rhodophyta)	SV40	lacZ	[59]
Glass bead agitation	Algal cells are activated by glass beads when DNA and polyethylene glycol are together.	<i>Neopyropia haitanensis</i> (formerly <i>Pyropia haitanensis</i>) (Rhodophyta)	SV40	lacZ; EGFP	[60]
Electroporation	–	<i>Ulva lactuca</i> (Chlorophyta)	CaMV 35S	GUS	(X [61].
Particle bombardment	–	<i>Undaria pinnatifida</i> (Phaeophyceae)	CaMV 35S	GUS	[45]
Particle bombardment	–	<i>Ulva australis</i> (formerly <i>Ulva pertusa</i>) (Chlorophyta)	UprbcS	EGFP	[62]

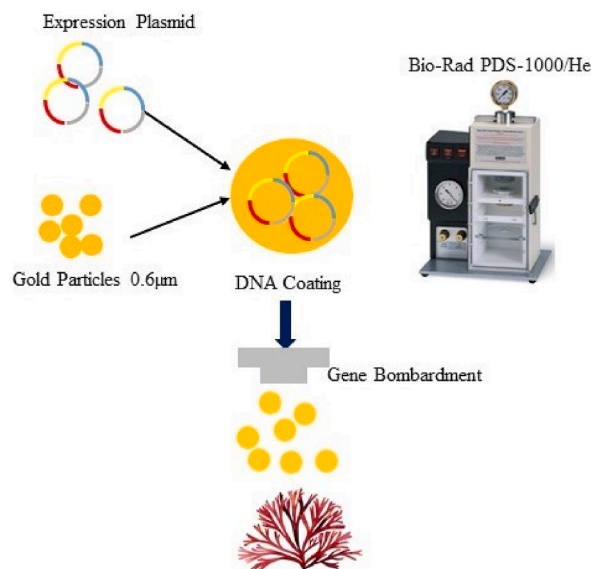


Fig. 5. Genetic transformation technique in *N. yezoensis* (Rhodophyta) [7].

engineering, which is still in its early stages.

4. Emerging methods facilitating seaweed aquaculture

4.1. Remote sensing

Data gathering in swampy locations, particularly macroalgal bloom mapping, can be complex since it typically requires special vehicles such as hovercrafts that are highly labour-intensive. Hence, new scientific and technological paths have surfaced to address these aquaculture challenges. One of the most efficient tools for monitoring is remote sensing, a supplement to field-based environmental monitoring. Long-term monitoring of the floating surface canopy of giant kelp was possible because of multispectral Landsat data [67]. Many kelp forest habitats, which provide critical services to both people and the environment, have experienced historical and continuous reductions, prompting the creation of this web tool. Using three Landsat sensors [68], created an enormous kelp canopy spatiotemporal dataset to investigate the impact of diverse period and site scales on long-term biomass changes.

The integration of optical and acoustic sensors in new autonomous vehicle technologies can provide quick, repeatable facilities across the surface of the water [69,70]. MODIS (Moderate Resolution Imaging Spectroradiometer) pictures were also an excellent source for mapping floating elements in different aquatic systems (C [71–73]).

To determine the optimal location for seaweed cultivation systems to prevent harmful algal blooms, using multi-sensor remote sensing data from satellite systems and in-situ observation, multi-temporal and multi-spatial evolution of *N. yezoensis* cultivation in the southern Yellow Sea [74].

The traditional remote sensing data processing technique has been transformed by the Google Earth Engine (GEE), a virtual solution for extensive geospatial information study. This platform gives customers access to advanced satellite image data (Landsat and Sentinel series satellites) and does image pre-processing on the cloud platform. One can track the spread of algae over time by incorporating the algae extraction algorithm. From 2007 to 2015 [75] used the mean distribution of *Ulva prolifera* in the South Yellow Sea using the FAI algorithm on MODIS imagery and statistical approaches according to the findings, *U. prolifera* had the most widespread coverage in 2015.

4.2. Computational fluid dynamics (CFD) analysis

CFD technique is an essential tool for simulating aquaculture systems by constructing aquaculture model systems. It can decrease assay time, lower manufacturing costs, and increase the quantity and quality of seaweed generation. Furthermore, the CFD model can account for biotic and abiotic elements influencing the seaweed habitat. More reliable data and evidence can be used to build a better solution for the proposed seaweed system. Hence it is an effective instrument for conducting parametric analyses to improve aquaculture systems.

[76] constructed a CFD model that enabled them to predict the velocity profile related to the flow of nutrients from monoline to tube net, demonstrating good nutrient availability in monoline mode, which led to better production. According to (Haro et al., 2020), CFD Simulation helps to speed up the process of a seaweed harvesting vessel by upgrading the conventional designs. Significant improvements in the shape of seaweed harvesting vessels can help to reduce lateral displacement, improve worker safety, and test

novel strategies. CFD simulations and model creation for the most significant cultivation parameters must be confirmed through laboratory/field experiments; the numerical results can aid in developing a better experimental design. These innovations will bring unlimited possibilities in seaweed genetic engineering, which is still in its infancy. Combining these innovations with the rapidly developing fields of systems biology and metabolic engineering will satisfy the demands related to energy, the environment, and human health.

4.3. Numerical modeling

Numerical modeling can help to maximize production by optimizing farm designs, cultivation techniques, and operational procedures and anticipating impacts on coastal ecosystems. Fig. 6 illustrates the application of advanced tools in seaweed farming.

For *Gelidium corneum* (formerly *Gelidium sesquipedale*) (Rhodophyta [77]) developed a dynamic model that forecasted NPP. Depth, production in relation to heat, respiration rates, brightness, output exudation, frond breakage, fatality, and a carbon-to-dry-weight conversion factor are considered in the model. The metabolism and growth rate of *Ulva* sp. were investigated using a mathematical model [78] in which one output file was generated for each month of the year while the model was running on a global 1° grid. Light intensity (I), temperature (T), salinity (S), dissolved nutrients (nitrate and phosphate), and respiration rate were used to compute the algal growth rate. The model presumption was that the rate of biomass increase was influenced differently by each environmental component [79]. developed a multi-scale model with variables such as climate, sunlight, and essential nutrients on an intense commercial farm for *Ulva* sp. (Chlorophyta) seaweed production and nitrogen absorption. It provides a critical alternative for environmental agencies and seaweed enthusiasts looking to extend their phytoremediation and seaweed production farms, enhancing ocean sustainability and the macroalgae-based economy [80]. developed the Macroalgal Cultivation Modeling System MACMODS, a macroalgae-specific computational modeling framework for evaluating within-farm fluctuations in sunlight, salinity flow, and nutrition fields on spatial and temporal scales. Models can help site selection for aquaculture activities, increasing blue growth.

5. Outlook and future perspectives

- Activities like urbanization, rapid industrialization, pollution of water bodies, and tourism in coastal areas affect seaweed growth. Even though seaweed production is economically viable, the blue economy concept is still a convincing argument for growing macroalgae.
- The intersection of biotech and aquaculture is positioned to cultivate macroalgae in a strategic convergence to keep up with the rising demand for food, fuel, and bio-product needs.

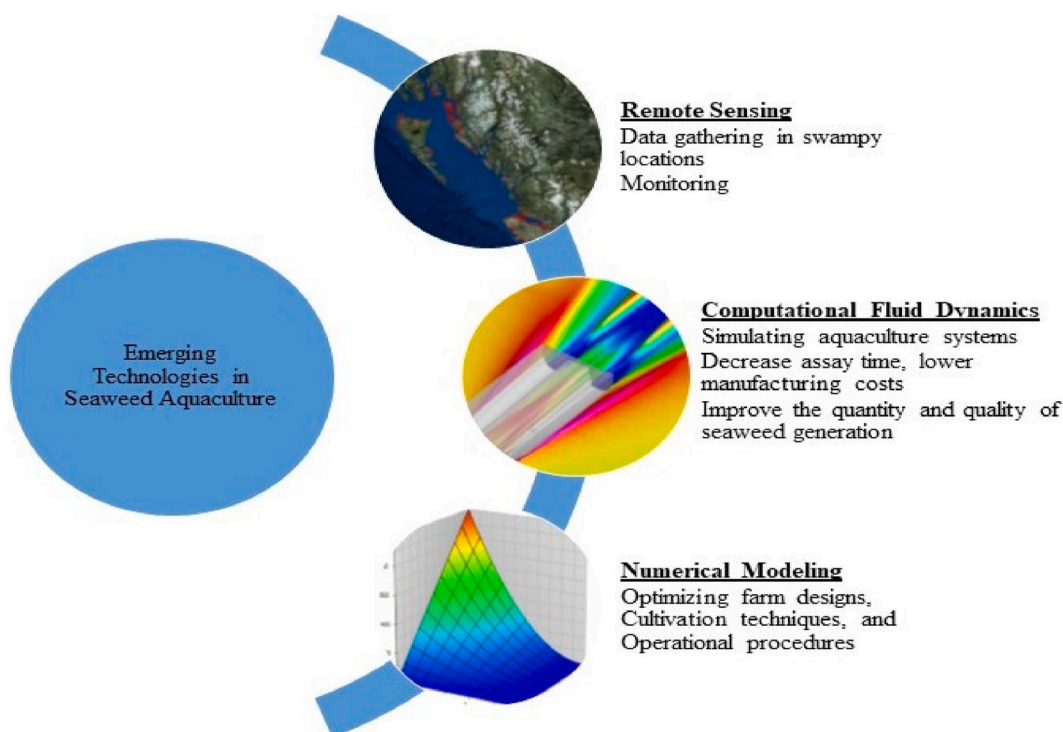


Fig. 6. Application of Advanced tools in seaweed farming.

- The advances in macroalgae biology and structural composition, microbiome sequencing, and computational approaches have substantially improved our understanding of microbiome diversity and the genes involved.
- Genome-based techniques are becoming increasingly prominent for examining and identifying novel gene functions in bacterial communities.
- Gene mutations are feasible by recognizing the genetic variants in producing metabolites and compounds. This must be done and applied with caution.

6. Conclusion

Seaweed can be grown in various ways; however, fundamental problems must be addressed for consistent yields to realize the prospective benefits of macroalgae farming. The following are the key outcomes from the review study:

- It is still challenging to adopt economically feasible and sustainable methods of seaweed cultivation in several regions of the globe while maintaining productivity. The macroalgae aquaculture industry has extensive challenges in terms of innovation.
- Nano-technology undoubtedly plays an essential role in aquaculture's growth and the longstanding feasibility of underutilizing seaweed cultivation. Using nanoparticles in macroalgae agriculture is a viable technique to achieve desired biomass output and high-value goods. We believe that nano-technology will alter aquaculture by focusing research and development toward achieving sustainable macroalgae farming with targeted efforts from governments and academics. However, its use will be recognized with further study and continued use.
- New possibilities for incorporating nano-technologies in the seaweed cultivation method should be investigated while considering potential environmental or human health risks. However, further investigation is strongly suggested to increase seaweed growth and the potential risk of using nanoparticles in macroalgae farming.
- To address biological challenges in seaweed cultivation, it is crucial to establish long-term genetic improvement strategies. Genetic engineering holds promise in bridging the gap between fundamental and applied seaweed science. By leveraging these advancements, new avenues can be explored in seaweed cultivation.
- Competency in seaweed biology, genetics, and metabolomics is required to optimize seaweed composition to reach large-scale production demands. In addition, it provides informed decisions regarding species selection, propagation, disease prevention, and sustainability.
- A new multidisciplinary approach must be evolved, combining existing seaweed scientific knowledge with computational tools and electronic sensors to efficiently control the complex biological process. It can reduce overall costs and enhance aquaculture productivity and efficiency. Numerous obstacles still exist to overcome in research and acceptance among the scientific community. However, continuous innovations in Seaweed farming are needed to cope with the changing world due to global climate change

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

No data was used for the research described in the article.

Declaration of interest's statement

The authors declare no competing interests.

Acknowledgements

This research is funded by the Universiti Malaysia Pahang (UMP) www.ump.edu.my Postgraduate Research Grant Scheme (PGRS) grant number: PGRS210348.

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