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The potential of seaweeds as a rich natural source for novel bioherbicide formulation/development

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Review

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Abstract

Recently, there has been emphasis on the need to shift away from the use of synthetic chemical herbicides to low-risk alternatives derived from natural sources. This is aimed at lowering or averting the negative impact synthetic herbicides have on the environment and dealing with the emergence of weed species resistant to these chemicals. As a result, more stringent measures or outright bans on the use of most synthetic herbicides have been put in place by regulatory bodies. As seaweeds are abundant resources in the marine environment that have the capacity to produce diverse bioactive compounds, they could serve as sustainably viable, natural, and low-risk alternatives/sources to explore for potential phytotoxic capabilities. This could in turn help to enhance or boost the availability of effective solutions in the global bioherbicide market. This review highlights the prospects of using seaweeds as novel biopesticides for the control and management of various plant pests, including weed species, and for the development of sustainable agriculture/forestry practices. More specifically, it focuses on their use as a rich natural source for novel bioherbicide development, a potential that has remained underexplored for many years. However, to unlock the full potential of seaweed-derived bioherbicides and to create a potential path toward their development, increased research and development efforts are urgently needed to tackle and overcome possible constraints posed in this novel area, such as variability in seaweed chemical composition, formulation technologies, stability and efficacy of seaweed bioactive compounds, cost and scalability, and environmental considerations.

Introduction

The occurrence of weed species and their damaging effects on the environment, including crop and forest plantations, is a global challenge that has resulted in huge losses to practitioners as well as other stakeholders in the agricultural and forestry sectors.

The use of synthetic herbicides, which have dominated the pesticide market for several years, has been the main protocol for tackling the damaging effects of invasive plant or weed species (Qu et al. 2021). Globally, glyphosate, a commercially available broad-spectrum and systemic postemergence herbicide (Tataridas et al. 2022), has to date been the most effective and widely used synthetic chemical treatment for the control and management of weed species (Kanissery et al. 2019; Wynn and Webb 2022). The economic losses that would be experienced by European Union (EU) farmers in the production of some major crops, including wheat (*Triticum aestivum* L.), potatoes (*Solanum tuberosum* L.), and grapes (*Vitis vinifera* L.), without the use of glyphosate are estimated at 24 billion kg (worth €10.5 billion), 10.4 billion kg (worth €2 billion), and 4.7 billion kg (worth €4.2 billion), respectively (Wynn and Webb 2022). However, there are problems associated with the use of synthetic herbicides, which includes non-target specificity as well as their nonbiodegradable nature, making them potentially hazardous to the environment and its inhabitants (Kanissery et al. 2019). An attempt to tackle their non–target specific nature, through the establishment of transgenic herbicide-resistant (HR) crops (Chahal et al. 2017), still has its limitations (Green and Owen 2011), as this intervention has aided the evolution and widespread nature of extremely problematic HR weeds in the environment (Duke 2011).

Approval for the use of glyphosate in the EU was recently renewed for 10 yr (Commission Implementing Regulation [EU] 2023/2660 of November 28, 2023), following a report by the European Food Safety Authority (EFSA) that revealed its active ingredient as showing no critical areas of concern with respect to endangering human and environmental health (Álvarez et al. 2023). However, EU biosecurity measures and sustainable development goals (Tataridas et al. 2022) are continually emphasizing the rational use of synthetic herbicides and the incorporation of natural herbicides (Álvarez-Rodríguez et al. 2023). Hence, there is a serious drive to identify eco-friendly and sustainably viable bioherbicides as natural alternatives for replacing or augmenting synthetic chemical herbicides.

Seaweeds are very important natural resources highly abundant along the Irish coastline and other coastlines across the world, with potential that is yet untapped or not fully exploited. The harsh competitive marine environment they thrive in, which constitutes several biotic and abiotic stressors (Hu et al. 2016), stimulates them to synthesize and host a wide array of bioactive molecules (Cikoš et al. 2021; Salehi et al. 2019) for adaptation and survival. These metabolites have given seaweeds and algae in general huge relevance, making them vital tools for natural product research applicable in several fields of study, including agriculture and forestry (Machado et al. 2019).

Studies on the possible use of seaweed extracts as novel bioherbicide sources is a relatively new area with very limited literature in this space (Chukwuma et al. 2023; Fonseca et al. 2012; Haniffa et al. 2021; Rifana 2019). It may be that using seaweeds for weed suppression is contrary to popular belief, because from ancient times farmers have utilized seaweeds as organic matter (fertilizers or fertilizer supplements) for the enhancement of yields of different crops (Taylor et al. 1993). Additionally, seaweeds are known to be very rich in micro- and macro-elements as well as other plant growth stimulatory molecules (Ali et al. 2021; Arioli et al. 2015; du Jardin 2015). As such, researchers have focused more on the beneficial effects of seaweed extracts on plant growth and development, either as a biofertilizer or plant biostimulant (Ali et al. 2021; Crouch and Van Staden 1992; Godlewska et al. 2016; Hassan et al. 2021; Hernández-Herrera et al. 2014; Vasantharaja et al. 2019), as opposed to their plant growth inhibitory properties. Nevertheless, as seaweeds are prolific producers of diverse and complex secondary metabolites such as polysaccharides, pigments, phenols, alkaloids, terpenes, among others (Arioli et al. 2015), some of which are halogenated (Güven et al. 2010; Salehi et al. 2019), they have shown a wide spectrum of biological properties, including phytotoxicity (Chukwuma et al. 2023; Fonseca et al. 2012; Haniffa et al. 2021). Interestingly, several studies have reported terpenoids/terpenes, phenolics, fatty acids and steroids as groups of bioactive compounds associated with phytotoxic activities (Araniti et al. 2017; Espinosa-Colín et al. 2023; Feitoza et al. 2018; Pardo-Muras et al. 2020, 2022). Seaweeds are known to produce these bioactive compounds (Gómez-Guzmán et al. 2018; Gunathilake et al. 2022; Salehi et al. 2019; Santos et al. 2019), which points to their capacity to serve as rich natural sources for novel bioherbicide formulation/development. This is also supported by several reports that have uncovered the allelopathic inhibitory effects of seaweeds on the same or other seaweed species, as well as other varying organisms occurring within the natural environment (Andras et al. 2012; Rasher and Hay 2010; Rasher et al. 2011; Sudatti et al. 2020; Vieira et al. 2016; Ye and Zhang 2013).

This review covers the use or application of seaweeds as biopesticides for sustainable agricultural/forestry pest management and focuses more specifically on their phytotoxic capabilities, which are indicative of their potential to be used as rich natural sources for novel bioherbicide development. Challenges to the development of bioherbicides from seaweeds and a potential path forward for the development of this research area are also discussed.

Seaweeds as Biopesticides for Sustainable Agricultural/Forestry Pest Management

The control of pests (including weed species) and diseases highly destructive to plants (crops and trees alike), remains a global issue. The use of chemically synthesized pesticides, which are known to persist in the environment, eventually accumulating and causing toxicities to the inhabitants (Buch et al. 2013; Chagnon et al. 2015), is gradually being phased out. However, they will continue to remain a priority in controlling plant pests and diseases until better or low-risk alternatives are readily available. Currently, synthetic chemical pesticides are now either being augmented or totally replaced with biological control agents (which are living organisms, e.g., microbes, natural enemies/predators, plant-incorporated protectants) or natural products (bio-derived compounds), popularly known as biopesticides (Copping and Menn 2000; Seiber et al. 2014).

The use of biopesticides rather than synthetic chemical pesticides is constantly gaining popularity around the globe because of their safety for non-target organisms and the environment in general and the relative ease of registering a biopesticide, especially in the United States (Copping and Menn 2000). According to DunhamTrimmer (2019), North America and Europe are regions with the largest share, with over 60% of the total global biopesticide market (Figure 1). The Latin American market was forecast to grow faster than any other region, possibly because climatic conditions and other environmental factors within the region seems more favorable for the application or use of biopesticides (Figure 1).

Research into the pesticidal properties of seaweeds will continue to remain relevant to the fields of agriculture and forestry (Machado et al. 2019; O'Keeffe et al. 2019b). Owing to the versatility of natural compounds present in seaweeds, there is no doubt that they are viable tools to help advance research in areas concerned with sustainable integrated pest management (IPM). The main aim of IPM is to drastically reduce or completely prevent the damaging effects of plant pests and diseases. The use of seaweed as a novel biopesticide encompasses biocidal properties. These properties include bioinsecticidal (Chanthini et al. 2021; Saber et al. 2018), biobactericidal/biofungicidal (Esserti et al. 2017, 2018; O'Keeffe et al. 2019a), bionematicidal (Ngala et al. 2016; Sultana et al. 2011), as well as bioherbicidal (Chukwuma et al. 2023; Fonseca et al. 2012; Haniffa et al. 2021) activities. Another group of biopesticides, known as biostimulants or biofertilizers, primarily protect plants by stimulating their growth and immunity against pests and diseases (Ali et al. 2021; du Jardin 2015).

There are clearly more studies in the literature that have revealed the biobactericidal or biofungicidal activities of seaweed extracts in comparison to those that have demonstrated other biopesticide properties. Unfortunately, studies on seaweed bioherbicidal activities, which is the focus of this review and will be discussed in detail later, has the least research output available in literature (Table 1), showing the need to increase research efforts in this novel area.

Bioherbicides

Bioherbicides, which are often called biopesticides, are important tools for integrated weed management. There are two major types

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Table 1. Bioherbicidal activities of seaweeds against plant/weed species.

Seaweed species	Extraction method/solvent(s)	Weed/plant species	Bioassay/bioactivity	Reference
Rhodophyta (*Mastocarpus stellatus* and *Porphyra dioica*) Phaephyta (*Fucus serratus* Linnaeus and *Fucus vesiculosus* Linnaeus)	Solvent extraction (maceration)/ water, methanol, ethyl acetate and *n*-hexane	*Lactuca sativa*, *Trifolium repens*, and *Lolium multiflorum*	Seed germination and plant growth Prolonged germination, inhibition of germination and plant growth, and chlorosis	Chukwuma et al. 2023
Sixteen (16) seaweed speicies comprising Rhodophyta, Phaeophyta, and Chlorophyta species	Ultrasonication/water	*Lactuca sativa*	Seed germination and plant growth Inhibition of germination and radicle growth	Haniffa et al. 2021
Rhodophyta (*Plocamium brasiliense*)	Solvent extraction (maceration)/ *n*-hexane, dichloromethane, ethyl acetate, and ethanol/ water (7:3)	Pasture weeds (*Mimosa pudica* and *Senna obtusifolia*)	Seed germination and plant growth Inhibition of seed germination, radicle elongation, and hypocotyl development	Fonseca et al. 2012
Phaeophyta (*Turbinaria ornata*) (Turner) J.Agardh and Chlorophyta (*Halimeda discoidea*) Decaisne	Solvent extraction (maceration)/ methanol	Radish seeds (*Raphanus sativus* L.)	Seed germination and plant growth Inhibition of seed germination and radicle growth	Rifana 2019

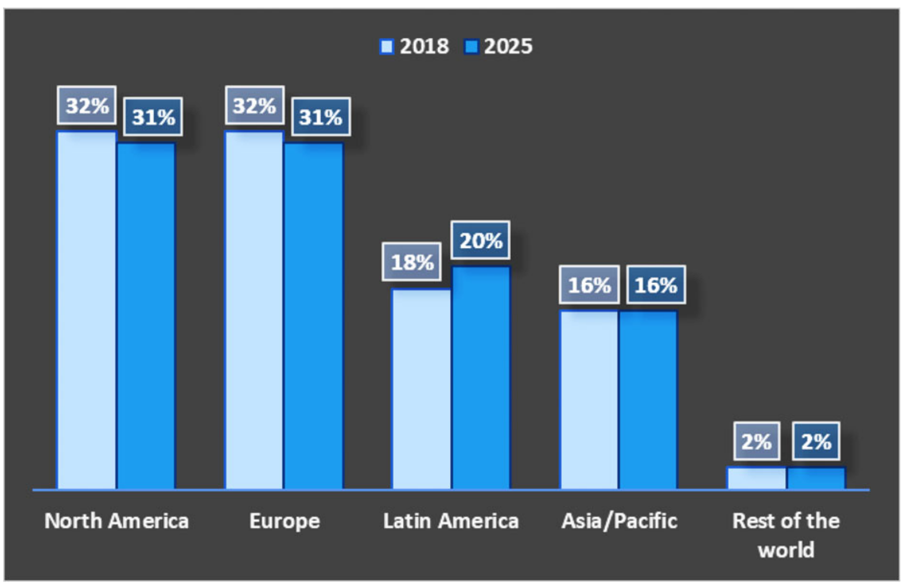

Figure 1. Biopesticide regional market share. (Modified from DunhamTrimmer 2019.)

of bioherbicides, some of which are already commercially available: (1) natural products or allelochemicals derived from plants or other natural sources, commonly referred to as biochemical bioherbicides; and (2) microbial bioherbicides, or more specifically fungal bioherbicides, also referred to as mycoherbicides (Kalia and Mudhar 2011).

Mycoherbicides are quite popular due to their ability to target host plants specifically and their easy application and production. Under standard laboratory conditions, these microbes are easily cultured and do not require highly specific nutrients for growth and mass production (Kalia and Mudhar 2011). Biochemical bioherbicides are also gaining popularity, because they are eco-friendly and target specific (Roberts et al. 2022). Biochemical bioherbicides use a variety of mechanisms/modes of action to unleash phytotoxic activities against weed species (Duke et al. 2022; Seiber et al. 2014). On the other hand, mycoherbicides have a basic mechanism of control that involves the invasion of vascular tissues once in contact with the host plant (Kalia and Mudhar 2011; Roberts et al. 2022). Additionally, microbial bioherbicides must first multiply and may have to compete with other microbes within the environment (Willoughby et al. 2014). Hence, their spread and action is usually too slow (Duke et al. 2022), and this could reduce their effectiveness as a biocontrol treatment (Willoughby et al. 2014). Moreover, if they spread successfully, the microbes can become native to the treated area, such that further application may not be needed, thereby, becoming a disincentive for commercialization (Duke et al. 2022). Kalia and Mudhar (2011) reported that under field conditions, mortality of weed plants caused by mycoherbicides was around 25% less compared with mycoherbicidal activity under laboratory conditions.

In light of this, the direct use of allelochemicals such as those that could be derived from seaweeds may possibly yield quicker herbicidal effects, as potent as or even more potent than those of synthetic herbicides. Furthermore, the tendency of natural compounds utilizing multiple mode(s) of action could help suppress or counteract the emergence of HR weed species (Duke et al. 2022; Seiber et al. 2014).

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Seaweed Extracts as Potential Novel Bioherbicides or Bioherbicide Sources

As highlighted earlier, minimal research efforts have been put into studying the use of seaweed extracts as potential bioherbicides or bioherbicide sources (Table 1). A study by Brain et al. (1977), which did not directly explore seaweed bioherbicide potential, demonstrated the possibility that seaweed extracts could possess such phytotoxic properties. In this study, seaweed extracts were reported to enhance the herbicidal effects of a synthetic chemical herbicide, an auxin-type compound called mecoprop (also known as methylchlorophenoxypropionic acid or MCPP), when in combination with the herbicide. One possible mechanism suggested in the study for the increased herbicidal activity was that certain seaweed bioactive compounds such as polysaccharides and cytokinins interacted with the herbicide, facilitating the absorption of the herbicide and further disruption of metabolism within the plant. This resulted in a shorter/faster weed kill time compared with when mecoprop was used alone (Brain et al. 1977).

In an earlier study, four crude extracts of the Brazilian red seaweed [*Plocamium brasiliense* (Greville) M. Howe & W.R. Taylor] were obtained using organic solvents of increasing polarity; *n*-hexane, dichloromethane, ethyl acetate, and ethanol/water (7:3) (Fonseca et al. 2012). These extracts, prepared to a concentration of 1% (w/v) were evaluated for any phototoxic activities against two pasture weed species, shameplant (*Mimosa pudica* L.) and sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby]. It was observed that the dichloromethane extract produced the strongest inhibition of seed germination by 35.0% and 14.0%, radicle elongation by 52.0% and 41.7%, and hypocotyl development by 17.1% and 25.5%, respectively, in *M. pudica* and *S. obtusifolia* (Fonseca et al. 2012). Previous work carried out by the same research group on the chemotaxonomic analysis of the Brazilian red seaweed and, more specifically, the fractionation of the dichloromethane seaweed extract, revealed richness in halogenated monoterpenes (Ferreira et al. 2010; Vasconcelos et al. 2010). Fonseca et al. (2012) suggested that the halogenated monoterpenes were likely responsible for or played a key role in the phytotoxic activities displayed by the extract.

In a recent study, in which a phytotoxic screen of a range of seaweed extracts were tested against lettuce (*Lactuca sativa* L.) seeds, the ethyl acetate extract of two Rhodophyta species, *Mastocarpus stellatus* (Stackhouse) Guiry (MEE) and *Porphyra dioica* J. Brodie & L.M. Irvine (PEE) were found to be most active in reducing lettuce seedling growth (Chukwuma et al. 2023). In pre- and postplant emergence assays in lab trials, the phytotoxicities of both extracts were further evaluated against the broad-leaf weed white clover (*Trifolium repens* L.) and the grass Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot]. Preplant emergence phytotoxic activities displayed by both active red seaweed extracts at a concentration of 5 mg ml^{-1} included a significant decrease in germination speed, significant inhibition of seed germination, and early seedling growth (Figure 2A and 2B). In the postplant emergence assay, overall plant growth was inhibited, and chlorosis of plant leaves, suspected to occur as a result of the inhibition of synthesis or enhanced degradation of leaf pigments, was also observed (Chukwuma et al. 2023; Figure 2C).

Several recent studies have attributed phytotoxic properties to various phenolic compounds (Espinosa-Colín et al. 2023; Facenda et al. 2023; Feitoza et al. 2018; Galán-Pérez et al. 2021; Pardo-Muras et al. 2020, 2022), in addition to their well-known antioxidant properties (Zeb 2020). In the study by Chukwuma et al. (2023), it was observed that the active red seaweed extracts (MEE and PEE) demonstrated significant levels of water-insoluble phenolic compounds, including phenolic acids and flavonoids. However, it was unlikely that the phenolics were solely responsible or played a major role in the observed phytotoxic activities, as the *n*-hexane extracts of the same red seaweeds, which also contained significant amounts of water-insoluble phenolics, displayed no inhibitory activities in the phytotoxic screen.

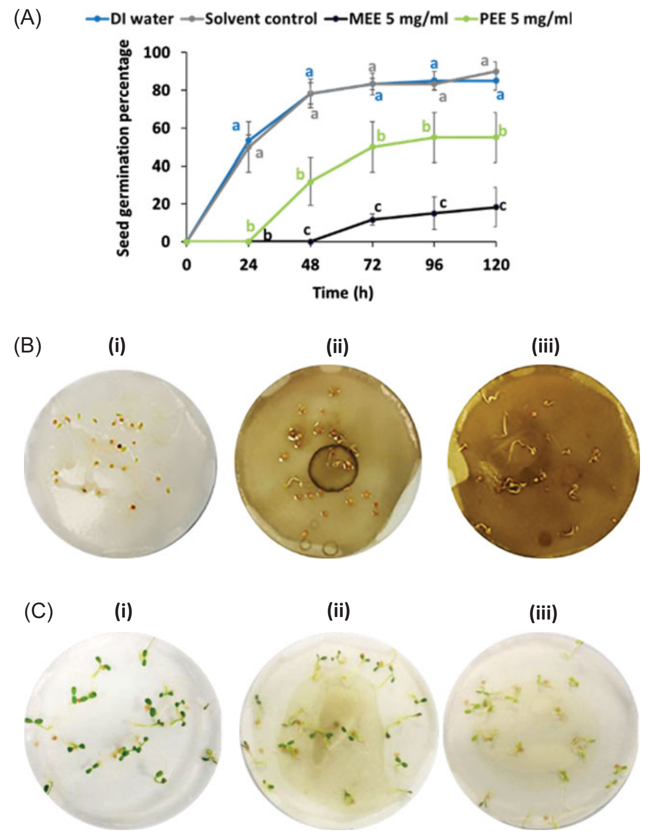

Figure 2. In vitro pre- and postplant emergence phytotoxicities of crude extracts of two red seaweeds (MEE and PEE). (A) Seed germination percentage in extract-treated and control plates over a 5-d period. (B, i and C, i) Solvent control plates; (B, ii and C, ii) MEE-treated plates; (B, iii and C, iii) PEE-treated plates. (Adapted from Chukwuma et al. 2023.)

In another study by Haniffa et al. (2021), it was reported that among 16 aqueous seaweed extracts (comprising red, brown, and green species) screened for allelopathic inhibitory activity on lettuce seeds at a concentration of 1,000 ppm, 7 of the extracts produced significant inhibitory effects on lettuce seed germination and radicle growth. The extracts of *Laurencia heteroclada* Harvey, *Caulerpa racemosa* (Forsskål) J. Agardh, and *Caulerpa sertularioides* (S. G. Gmelin) M. Howe exhibited the strongest inhibition of lettuce seed germination, resulting in germination percentages of 17.5%, 25%, and 18%, respectively, values significantly lower than the distilled water control (85.0%). The extract of *C. racemosa* produced the strongest plant growth inhibitory effect, resulting in the smallest mean radicle length of 0.63 ± 0.197 cm, which was also significantly smaller than the control (3.33 ± 0.172 cm) (Haniffa et al. 2021). Having produced the most significant inhibition on seed germination, bioactive compounds present in the active red seaweed (*L. heteroclada*) extract were further isolated and identified to include nonaromatic cuparane, algoane, caulerpin, cholesterol, and a new brominated nonaromatic isolaurene-type

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Table 2. Some bioactive compounds derived from plant or microbes associated with phytotoxic properties.

Bioactive compounds	Plant/microbial source	Phytotoxicities	Reference
Polysaccharides/ glycopeptide	*Corynebacterium sepedonicum* and *Cryphonectria parasitica*	Wilting of plant leaves and necrosis	Corsaro 1998; Strobel 1967
Long/middle/short-chain/ essential fatty acids	Animal waste (hog and dairy manure) and Southern cattail (*Typha domingensis* Pers.)	Decrease in the amount of polar lipids, and chlorophyll, electrolyte leakage, severe damage to cell and thylakoid membranes; inhibition of germination, α-amylase activity, and physiological water uptake; inhibition of growth	Edney and Rizvi 1996; Fukuda et al. 2004; Gallardo-Williams et al. 2002
Phenolic compounds	*Typha domingensis*, Common gorse (*Ulex europaeus* L.), and Scotch broom [*Cytisus scoparius* (L.) Link]	Inhibition of germination, growth, and chlorophyll production	Gallardo-Williams et al. 2002; Pardo-Muras et al. 2020, 2022
Essential oils/terpernoids	Blackboard or devil tree [*Alstonia scholaris* (L.) R. Br.] and carline thistle (*Carlina acaulis* L.) (Asteraceae)	Inhibition of germination, radicle growth, and functioning of photosystem II; leaf necrosis, reduction of relative water content and total leaf area, and disruption of the photosynthetic machineries	Álvarez-Rodríguez et al. 2023; Wang et al. 2014
Amino acid, ʟ-3,4-dihydoxyphenylalanine (ʟ-DOPA)	Velvetbean [*Mucuna pruriens* (L.) DC.]	Inhibition of growth by influencing amino acid metabolism and deregulating metal homeostasis, especially that of iron, which is required for fundamental biological processes	Fujii 2003; Golisz et al. 2011

sesquiterpene. However, only algoane showed moderate activities against lettuce seed germination and radicle growth, when the pure compounds (solvated in methanol and prepared to a concentration of 1,000 ppm) were individually tested for phytotoxic activities. It was suggested that two or more components of the active aqueous red seaweed extract acted in synergy or were required to elicit the phytotoxic effects observed (Haniffa et al. 2021).

Several different classes of natural products or secondary metabolites derived particularly from plants or microbes have been associated with varying phytotoxic activities (Table 2). Seaweeds have been shown to be a rich source of these bioactive compounds, as well as being prolific producers of more diverse and complex biomolecules (Gómez-Guzmán et al. 2018; Gunathilake et al. 2022; Salehi et al. 2019; Santos et al. 2019). This indicates that further exploration into establishing seaweed phytotoxic potential and an increased effort in the development or formulation of seaweed-derived bioherbicides would likely yield desirable/positive outcomes.

The Current Bioherbicide Market and Possible Constraints to the Development of Seaweed-derived Bioherbicides

Progress made on the identification and development (or formulation) of new bioherbicides has been quite slow, and there is a long way to go before they significantly impact the market as compared with the other biopesticides (bioinsecticides, biobactericides/biofungicides, and bionematicides) (Marrone 2024; Seiber et al. 2014). This might be partly due to the availability of glyphosate, a synthetic herbicide that has dominated the herbicide market for many years. This significantly reduces the overall value of the market and in turn results in a relatively reduced effort in the discovery of bioherbicides (Duke et al. 2022). It might also be in part due to the inconsistency in the performance of “potential” bioherbicides under field conditions, and as such, few have achieved long-term commercial success (Cordeau et al. 2016).

Bioherbicides were first commercially available in the 1980s (Cordeau et al. 2016). Although, the number of biopesticides has increased globally since then, bioherbicides still occupy an insignificant share, just 1% of the total market share of all biopesticides (DunhamTrimmer 2018; Marrone 2024). In 2016, it was reported that there were about 15 duly registered bioherbicides available in the market (Cordeau et al. 2016). However, due to recent advances in the field of bioherbicide development, the number has increased to 23, most of which are commercially available in the United States, Canada, Australia, and Asia, with only 1 in Africa, while 2 are available in Europe: 1 in Belgium and 1 in France (Roberts et al. 2022). Addition of about seven new bioherbicides to the market between the years 2016 and 2022 is relatively slow progress, again indicating the need to intensify research efforts in this area. However, in a recent review, Marrone (2024) reported about 11 companies developing new bioherbicides, mostly based on metabolites, and some new innovative biotechnologies such as RNA interference (RNAi) and peptides; 3 of these companies (Bioprodex, Biohelp, and the Toothpick Project) have products already commercially available. It should be noted that the majority of these commercially available bioherbicides were derived from plants or are microbial-based. Therefore, it is envisioned that as seaweeds are abundant natural resources, further exploration into their use as potentially novel bioherbicide sources would greatly boost or enhance bioherbicide development and help increase available options.

As with any potential source of bioactive compounds, there are some limitations or challenges worth mentioning that could impede the development or formulation of bioherbicides from seaweeds. Some of them are described in the following sections.

Variability in Chemical Composition

Seaweeds are morphologically complex organisms with diverse chemical compositions that vary greatly depending on factors such as seaweed species, location of habitat, and environmental conditions. These factors could influence variable extraction yields, which might indicate an alteration in the availability or concentrations of the desired bioactive compound(s), and could in turn lead to reduction or loss of efficacy (Afonso et al. 2021; Aroyehun et al. 2019; Arunkumar and Sivakumar 2012; Marinho-Soriano et al. 2006; Sanz et al. 2023; Tan et al. 2012). Thus, it is challenging to standardize the extraction process and ensure consistent bioherbicide formulations with predictable concentrations of the desired bioactive compounds. This is why the application of natural product discovery strategies such as bioactivity-guided isolation or fractionation-driven bioassay (Duke et al. 2000), which aid the isolation and identification of the responsible bioactive compound(s) in such active extracts, is an important step in the research and development process. However, in many cases, desired activity is often lost or greatly diminished when the diversity and complexity of molecules in crude extracts are simplified to yield individual compounds (Duke et al. 2000).

Regulatory Approval

The regulatory approval process for bioherbicides as with all other biopesticides can be time-consuming, capital intensive, and high risk (Marrone 2024). Seaweed extracts or their bioactive compounds for potential use as bioherbicides would need to undergo rigorous ecotoxicological testing for safety or undesired environmental impact before obtaining regulatory approval for commercial use. As natural compounds, they are expected to be eco-friendly and have a shorter half-life than synthetic chemical herbicides (Cordeau et al. 2016; Duke et al. 2000). However, such natural phytotoxins that could potentially be derived from seaweeds may not be completely harmless to other non-target life forms, including mammals (Cordeau et al. 2016), and their spectrum of biological activity should be carefully evaluated (Duke et al. 2000). In fact, natural compounds have been noted to be some of the most potent mammalian toxins (Duke et al. 2000). Interestingly, the red seaweed species especially, are known to produce bioactive compounds usually associated with halogen atoms (Sudatti et al. 2020). For example, *Asparagopsis taxiformis* (Delile) Trevisan and *Asparagopsis armata* Harvey are two Rhodophyta species known for the production of the bromoform ($CHBr_3$), an antimethanogenic compound that is currently being considered a potential ecotoxicological risk and could have other damaging effects in the environment, such as ozone layer depletion (Glasson et al. 2022; Jia et al. 2022). It is important to note that the presence of a halogen substitute in the structure of synthetic herbicides has aided their increased persistence (half-life) and environmentally toxic properties (Soltys et al. 2013).

Formulation and Stability

Developing stable and effective formulations of bioherbicides from seaweeds can be challenging. Appropriate formulation techniques such as encapsulation, emulsification, or the addition of adjuvants (Ash 2010; Cordeau et al. 2016; Hallett 2005; Marrone 2019; Roberts et al. 2022; Seiber et al. 2014; Campos et al. 2023) may be required to enhance the solubility, stability/shelf-life, and efficacy of the specific bioactive compound against target weeds, and to protect it from adverse environmental conditions. There are reports that have shown inconsistency or failure of potential bioherbicides to replicate in field or greenhouse studies the phytotoxic activities previously displayed in vitro (in lab trials), possibly due to soil conditions/microbial activities or other environmental conditions (Travaini et al. 2016). Hence, conducting tests that yield positive results from mimicking real-world situations is needed. Such reduction or loss of efficacy could be a consequence of poor formulation, which could affect certain properties of the natural compounds or enhance their biodegradation in the field (or soil) after application (Chuah et al. 2013; Facenda et al. 2023; Galán-Pérez et al. 2021). Poor storage of the extractable materials or the crude extracts generated from them has also been shown to affect stability as well as efficacy of the bioactive compounds they contain (Laher et al. 2013; Srivastava et al. 2007; Stafford et al. 2005). This is due to the occurrence of reactions (influenced by storage conditions) that could chemically modify the bioactive compounds, thereby altering their composition or concentration.

Cost and Scalability

Another challenge is the cost of seaweed extraction, formulation, and production. In general, marketing/commercialization cost of bioherbicides is relatively high compared with cheaper and already commercially available synthetic herbicides (Ash 2010; Stefanski et al. 2020). There is no doubt that the research and development of seaweed-derived bioherbicides through to commercialization would be highly capital intensive, as previously noted for other bioherbicides/biopesticides in the market (Marrone 2019, 2024). Moreover, large-scale seaweed farming, harvesting, and processing is labor intensive and requires significant investment in infrastructure and equipment. This could be disincentivizing or affect the profitability of producing such seaweed-derived bioherbicides on a commercial scale (Soltys et al. 2013). Hence, cost-effective and scalable seaweed production methods need to be developed (Kite-Powell et al. 2022) to make bioherbicides that could be potentially derived from seaweeds commercially viable and sustainable. This is why relevant support through increasing available government or private sector funding to universities and research institutions and more investments in start-ups involved in the area of bioherbicide formulation or development would be key for any progress to be made (Marrone 2024).

Environmental Considerations

Continuous large-scale seaweed harvesting to sustain production could have potential environmental or ecological impacts on biodiversity and on the marine environment as a whole. Although, the allelochemicals derived from seaweeds are generally considered environmentally friendly alternatives to chemical herbicides, careful monitoring and mitigation measures need to be in place to ensure sustainable and environmentally responsible production practices. The development of seaweed aquaculture production systems is a vital approach to recovery or replacement of such depleted seaweeds (García-Poza et al. 2020; Kim et al. 2017). Additionally, new techniques, including synthetic biology, molecular biology, genomics, metabolomics, among others (Marrone 2024; Soltys et al. 2013), are important tools that have been applied to identify genes of interest in order to engineer fast-growing organisms in the lab to yield such phytotoxic compounds with reduced/no environmental considerations.

Weed Spectrum and Efficacy

The efficacy of seaweed extracts or the specific bioactive compound(s) as a bioherbicide may vary depending on the type of weeds targeted (Chukwuma et al. 2023), and they may not be very effective against a wide range of weed species. This could be as a result of the yield of extract obtained or, more specifically, the concentration of responsible bioactive compound(s) present in the seaweed extract, which may be low (requiring excessive extraction). Thus, their phytotoxicities may be short-lived and lack long-term impact. As such, further research is needed to identify the active compounds and determine the spectrum of weeds that can be effectively controlled by seaweed-derived bioherbicides.

Prospects/Path Forward

Bioherbicides are very important tools for sustainable agricultural or forestry practices. Expansion of their role in integrated pest (weed) management necessitates an increased effort in searching for new potential bioherbicides and assessing their efficacy in the field (Cordeau et al. 2016). Undoubtedly, natural compounds used as insecticides or fungicides with new molecular targets have gained more acceptance and achieved more commercial successes compared with those used as bioherbicides (Duke et al. 2022). However, bioherbicides such as those that could be derived from seaweeds have high potential impact and would likely gain traction in the market in the coming years. This is owing to the fact that 40% of the chemical pesticide market is currently herbicides (Marrone 2024). Moreover, no new synthetic herbicide with a significant mode(s) of action has been introduced or commercialized in the last 20 to 30 yr (Marrone 2024; Qu et al. 2021; Seiber et al. 2014), and with many being banned from use, there is room within the market for the rapid development and growth of bioherbicides. Unlike synthetic herbicides, natural compounds (or phytotoxins) have been shown to have several molecular targets or utilize multiple modes of action, indicating that they have potential to help cope with or eventually overcome the growing population of HR weeds (Dayan et al. 2015; Duke et al. 2000, 2022; Seiber et al. 2014). The potential of natural compounds for having longer persistence and stronger potency than living microbes (easily constrained by environmental factors), positions them as more exciting and promising tools to explore as new bioherbicide options (Marrone 2024).

Therefore, the versatility and quantity of secondary metabolites noted to be present in seaweeds make them a preferred, sustainably viable option to explore as potentially novel bioherbicide sources to help increase the number of effective solutions available in the bioherbicide world market today. A report by the International Market Analysis and Research Consulting (IMARC) group forecast a compound annual growth rate of 12.8% for the global bioherbicide market between the years 2023 and 2028 (IMARC n.d.). This means that by 2028, the market is expected to reach a value of US$5 billion compared with its value as of 2022, which stood at US$2.4 billion (IMARC n.d.). This anticipated increase in the value of the market size of bioherbicides could be easily attained or surpassed through intensifying research and development efforts in areas exploring the use of seaweeds as potential bioherbicide sources.

Seaweeds are abundant natural resources along coastlines across the globe that have diverse chemical composition and bioactive properties. Reports on different seaweed species using allelochemicals to compete with one another and other varying organisms (An et al. 2008; Andras et al. 2012; Rasher and Hay 2010; Rasher et al. 2011; Sudatti et al. 2020; Vieira et al. 2016; Ye and Zhang 2013) signifies great potential for their use as bioherbicide sources. However, the limitations and challenges highlighted need to be addressed. According to Ash (2010), the major constraints to bioherbicide development and commercialization could be overcome by synergizing and providing a clear path in the processes involving scientific research and the business (product development and marketing) aspects of it, such that intellectual property is shared equitably among all parties involved. Most importantly, research, development, and regulations are required to overcome these constraints. This would help in harnessing and maximizing the full potential of deriving bioherbicides from seaweeds for use as novel, sustainable, and environmentally friendly alternatives to synthetic herbicides, and to increase available effective bioherbicides.

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