Use of Seaweed in Agriculture: Evaluation in Terms of Sustainability and Efficiency

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***Abstract*— Seaweeds (macroalgae) are organisms that play vital roles in the marine ecosystem and contain many biochemical compounds for human use. Seaweeds are widely used in crop production due to the presence of plant growth-promoting compounds and are natural resources of increasing importance in sustainable agricultural practices. However, the presence of various growth factors in seaweeds, as well as salts and metallic elements with potential toxicity, limits the full utilisation of the potential of most of these products as biofertilizers. In this study, the production of seaweeds in the world, their properties, utilisation in agriculture, potential benefits and problems encountered were evaluated.**

***Keywords*— Seaweed, Biofertilizer, Sustainable Agriculture.**

I. Introduction

Seaweeds include macroscopic, multicellular marine algae that commonly inhabit the coastal regions of the world's oceans where suitable substrates exist. Macroalgae are photosynthetic aquatic organisms and are mostly divided into three main groups: Chlorophyta (green algae), Phaeophyceae (brown algae) and Rhodophyta (red algae). Due to the known benefits of seaweeds as a source of organic matter and fertiliser nutrients, they have been used as soil conditioners in agriculture for centuries [1]. The environmental and ecological impacts of chemical inputs used in conventional agriculture have increased the trend towards alternative and sustainable solutions. In this context, seaweed-based products have attracted attention due to their ability to promote plant growth, increase stress tolerance and enrich soil microbiota [2]. Numerous studies have demonstrated that seaweed applications have a wide range of beneficial effects on crops, such as early seed germination, increased yield, higher resistance to biotic and abiotic stress factors, and extended postharvest shelf life of crops. In addition, seaweeds are biodegradable, non-toxic and natural, making them an environmentally friendly option [3] .

Brown seaweeds are the most widely used species used as biofertilizers in agriculture, including about 2,000 species that reach maximum biomass levels on rocky shores of temperate regions. Worldwide, about 35 million metric tonnes of seaweed (wet weight) are produced annually [4], a significant portion of which is used as nutritional supplements and biostimulants or biofertilizers to enhance plant growth and yield.

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In this paper, academic studies and field applications on the effects of seaweed on plants and its agricultural applications are reviewed.

II. World Seaweed Production

Seaweeds (macroalgae) are found in all seas of the world, but grow most densely and productively in temperate and cold seas. Seaweeds (macroalgae) are produced worldwide by both natural collection and culture (aquaculture). The most commonly produced species are red seaweeds (Rhodophyta), brown seaweeds (Phaeophyta) and green seaweeds (Chlorophyta) which are of less commercial importance.

Especially Asian countries provide most of the current production in the world. Tanzania, Vietnam and Madagascar are the rising countries in seaweed production in recent years. Approximately 35 million tonnes (wet weight) of seaweed is produced annually in the world. Approximately 97 per cent of this was obtained through culture and 3 per cent through collection from natural sources. The top 6 seaweed producing countries in the world are presented in Table 1 [4]. Only China and Indonesia meet about 85% of the total production.

TABLE I:
SEAWEED PRODUCTION WORLDWIDE [4].

Country	2022 Production (wet weight, tonnes)	Rate (%)
China	~19.8 million tonnes	~56%
Indonesia	~10.2 million tonnes	~29%
Korea (South)	~1.8 million tonnes	~5%
Philippines	~1.5 million tonnes	~4%
Japan	~600 thousand tonnes	~2%
Chile	~400 thousand tonnes	~1%

III. Uses of Seaweed

Seaweed production has received global attention in recent years as it is recognised as a carbon sink and sustainable protein/bioactive source. It is used directly as a food ingredient (sushi nori, salads) and indirectly for human consumption as food additives (gelling additives: agar, carrageenan, alginate). Seaweed biofertiliser is used in agriculture as a soil conditioner and plant growth regulator; in cosmetics and pharmaceuticals production due to its antioxidant and anti-inflammatory components; in the energy sector as a potential source for bioethanol and biogas production; and as animal feed due to its effect on reducing methane production in ruminants (especially Asparagopsis taxiformis). In addition, its use in industrial areas such as bioplastics and biofertilizers is rapidly expanding. The main species produced, areas of use and producer countries are given in Table 2.

IV. Chemical Properties

The use of mycorrhizal fungi in sustainable agriculture plays a critical role in plant nutrition and health, soil quality protection, carbon sequestration, reduced need for chemical inputs and environmental sustainability.

A. Polysaccharide Content

Seaweeds contain plenty of water-soluble polysaccharides in their structure. For example, agar and carrageenan obtained from red seaweeds are used as gel formers and stabilisers in the food industry, while alginate obtained from brown seaweeds is used in the textile and pharmaceutical industries [6].

B. Minerals and Vitamins

Seaweeds contain high levels of minerals such as iodine, calcium, magnesium, iron as well as vitamins A, C, E and B complex. It is especially rich in iodine, which is important for thyroid health [7]

C. Pigments

In addition to chlorophyll, algae contain pigments such as fucoxanthin (in brown algae) and phycobilin (in red algae). Fucoxanthin attracts attention with its antioxidant and anti-obesity effects [8].

V. Biological Properties

A. Antioxidant Activity:

Polyphenols and carotenoids found in seaweeds have strong antioxidant effects. These compounds prevent cell damage by neutralising free radicals [9].

B. Antibacterial and Antiviral Effects:

Some macroalgae species produce antimicrobial compounds effective against human pathogens. Thanks to these properties, they have the potential to be utilised in medical and pharmaceutical fields [10].

VI. Use of Seaweeds in Agriculture

Seaweeds are increasingly being used as biofertilizers in organic agriculture due to their mineral content, plant growth promoting properties and resistance to stress conditions [3]. The general effects of seaweeds on plants and soil are summarised below:

A. Fertilizer Effects

Seaweeds can significantly support the mineral nutrition of plants since they contain high levels of macro and micronutrients (K, Ca, Mg, Fe, Zn, etc.). By increasing microbial activity in the soil, it improves soil health and supports its fertility. Improves soil physical and chemical properties by enriching the organic matter content in the soil. Application of seaweed extracts to soil promotes plant growth by stimulating the growth of beneficial soil microbes and the secretion of soil regulators by these microbes.

B. Plant Growth Promoting Biostimulant Effect

Seaweed products contain natural phytohormones (auxin, cytokinin, gibberellin) that accelerate root growth, increase leaf area and promote flowering and fruit set.

C. Stress Tolerance and Immune System Strengthening Effects

Polyphenols and carotenoids found in seaweeds have strong antioxidant effects. These compounds prevent cell damage by neutralising free radicals [9]. In particular, it increases plant resistance to abiotic stress factors such as salt, drought, heavy metal pollution [11]. Seaweeds enable plants to tolerate oxidative stress by activating antioxidant enzymes. Phenolic compounds and polysaccharides enhance disease resistance by strengthening plant immunity. Osmoregulatory compounds such as mannitol and betaine increase plant resistance to stress conditions (drought, salinity).

D. Increases yield and quality in crop production

Seaweed preparations applied to soil and leaves provide improvement in quality criteria such as fruit size, taste and aroma. Significant yield increase has been observed especially in high economic value crops such as tomato, pepper, vineyard and wheat.

E. Use in Natural Pest Management

Some macroalgae species produce antimicrobial compounds effective against pathogens. Due to their antibacterial and antiviral properties, they have the potential to be used in the fields of medicine and pharmacy [10]. In agricultural applications, some seaweed species have antifungal and antibacterial effects. Especially seaweed extracts applied foliarly show protective effect against some fungal diseases (e.g. Botrytis, Pythium).

F. Compatibility with Sustainable Agricultural Practices

Seaweed products protect the ecological balance by reducing the use of chemical fertilisers and pesticides in crop production. In this respect, it is one of the inputs allowed for use in organic agriculture. Seaweed applications reduce the environmental burden by reducing the carbon footprint.

VII. Risks of Seaweed Products in Agricultural Use

Seaweeds are widely used in agriculture as biostimulants and biofertilizers that promote plant growth. However, in some cases, negative effects may also occur. These effects are explained in below:

A. Salt Content and Soil Salinisation Risk

Seaweeds can contain high amounts of salts such as sodium and chlorine. Excessive and uncontrolled applications, especially when used without washing, may cause salt accumulation in the soil. This increases soil salinity and adversely affects plant root development [2,3].

B. Excessive Hormone Effect (*Phytohormone* Imbalance)

Seaweed extracts naturally contain plant hormones such as auxin, cytokinin, gibberellin. However, when used in high doses, these hormones can cause abnormal growth, late flowering or impaired fruit set in plants [3].

C. Microbial Imbalance

Continuous application of seaweed extracts to soil can destabilise the balance of the indigenous microbial fauna. In particular, it may adversely affect the fungal-based biological balance and cause pathogenic organisms to become dominant [12].

D. Risk of Heavy Metal Accumulation

Some seaweeds can absorb heavy metals (e.g. arsenic, cadmium, lead) from the marine environment. The use of these seaweeds as fertiliser can cause heavy metal contamination in the soil and these metals can accumulate in the soil, negatively affecting both plant health and human health through the food chain [13].

E. Economic and Practical Limitations

High quality seaweed extracts are costly due to limited production areas and multiplicity of production processes. Supply and transport costs are high, especially in regions without local production. In addition, they may not have a positive effect on all plants and soil types or their effects may be uncertain or temporary in some applications.

F. Plant Nutrition Imbalance and Phytotoxicity

Seaweeds may contain high amounts of some microelements (e.g. iodine, boron). Excess of these elements can disturb the micronutrient balance in the soil and lead to toxicity [14]. Especially when applied in high concentrations, seaweed extracts can have phytotoxic effects on some plants (e.g. leaf burns or impaired root growth). This is often the result of overdosing or application to sensitive species [15].

Seaweed products can be very useful when used in the correct content and dose. In order to avoid the aforementioned negativities, the dosage and frequency of application should be carefully determined according to the soil and crop conditions, heavy metal analyses of seaweed products should be performed and the values should be within the reliable range, and forms with reduced salt content should be preferred in the application. This requires careful standardization of seaweed products and development of product-specific application norms

VIII. Conclusion

Seaweeds are not only a source of nutrients in agriculture, but also a solution that improves plant health, increases yield and is environmentally friendly. Agricultural use of seaweeds has a strategic importance especially in today's world where problems such as climate change and soil exhaustion are increasing. Seaweeds have the potential for versatile use due to both their chemical content and biological effects. The use of seaweeds as biological-based inputs in crop production can significantly contribute to both reducing environmental impacts and increasing food security. However, the negative impacts encountered in the agricultural use of seaweed products, the standardization of these products and their compliance with agricultural legislation require further regulation.

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