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Contribution of macroalgae (seaweed) to sustainability

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Abstract

This paper surveys how macroalgae (seaweed) can advance several Sustainable Development Goals (SDGs). By enhancing food security, sequestering carbon, supplying biomass for clean energy, filtering polluted water and replacing wood- or petroleum-based materials, seaweed directly supports SDGs 2, 6, 7, 12, 13, 14 and 15 while fostering innovation and infrastructure (SDG 9). Cultivation projects also generate local jobs—especially for women—thus contributing to SDGs 1, 4, 5, 8, 10 and 16. Key bottlenecks remain: high production costs, limited technology, insufficient research–industry coordination and patchy policy frameworks. The paper details these obstacles in the introduction and offers campus-, national- and global-scale recommendations in the discussion.

Keywords: Sustainability, Macroalgae, Sustainable Development Goals, Seaweed-Based Biofuel, Water Quality.

Makroalglerin (deniz yosunlarının) sürdürülebilirliğe katkısı

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Özet

Bu çalışma, deniz yosunu (makroalg) temelli uygulamaların birden çok Sürdürülebilir Kalkınma Amacı'na (SKA) eş zamanlı katkı sağlayabileceğini göstermektedir. Makroalgler; gıda güvenliğini arttırma, karbon tutma ve biyoyakıt üretimi yoluyla iklim eylemine (SKA 13) ve temiz enerjiye (SKA 7) destek olma, atıksu arıtımı ve deniz ekosisteminin iyileştirilmesiyle temiz suya (SKA 6) ve "Sudaki Yaşam"a (SKA 14) hizmet etme, ayrıca alternatif hammadde sunarak ormansızlaşmayı azaltma (SKA 15) gibi potansiyellere sahiptir. Bu süreçler aynı zamanda sorumlu üretim-tüketimi (SKA 12) ve sürdürülebilir sanayi-altyapıyı (SKA 9) teşvik eder; yeni istihdam alanları yaratarak yoksulluğun azaltılmasına, toplumsal cinsiyet eşitliğine ve kapsayıcı ekonomik büyümeye (SKA 1, 5, 8, 10) katkı sunar. Bu potansiyele karşın, maliyet etkinliği, teknolojik altyapı, bilimsel iş birliği ve politika geliştirme konularındaki yetersizlikler önemli engeller oluşturmaktadır. Makalenin girişinde bu zorluklar özetlenmiş, tartışma bölümünde kampüsten küresel ölçeğe somut çözüm önerileri geliştirilmiştir.

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Anahtar Kelimeler: Sürdürülebilirlik, Makroalgler, Sürdürülebilir Kalkınma Amaçları, Deniz Yosunu Tabanlı Biyoyakıt, Su Kalitesi.

1. Introduction

Oceans, covering approximately 75% of the Earth's surface, represent the planet's largest ecosystem. Within these marine environments, algae serve a pivotal role as primary producers, forming the base of aquatic food webs. Given their ecological importance, this study focuses on the sustainability potential of algae. Algae are photosynthetic eukaryotic organisms that exist in both unicellular (microalgae) and multicellular (macroalgae) forms. While each type offers distinct characteristics and applications, this research narrows its scope to macroalgae to enable a more focused investigation. Although their biological processes differ, both microalgae and macroalgae contribute meaningfully to the achievement of the United Nations Sustainable Development Goals (SDGs). The primary objective of this study is to examine the sustainability applications of macroalgae and to assess their potential impact across various domains.

Macroalgae, commonly referred to as seaweed, are taxonomically classified into three primary groups: blue-green algae, red algae, and brown algae. Understanding this classification is essential for identifying their potential applications. For instance, red and brown algae are particularly valued for their therapeutic properties, thereby contributing to the promotion of good health and well-being, in alignment with Sustainable Development Goal (SDG) 3. Additionally, various macroalgae species possess distinct nutritional profiles and uses that support SDG 2 (Zero Hunger). *Porphyra* spp. (red algae), for example, is widely utilised in the preparation of soups, sushi wraps, snacks, vegetable-based dishes, beef meals, and fish curries. Similarly, *Sargassum* spp. (brown algae) and *Cladophora* spp. (green algae) are consumed as sea vegetables.

In the context of biofuel production, specific macroalgae species support SDG 7 (Affordable and Clean Energy) by serving as sources of renewable energy. *Ulva intestinalis* (green algae) is used in biodiesel generation, while *Sargassum* spp. is employed in the production of bioethanol.

In summary, taxonomic knowledge is vital for the sustainable management and utilisation of macroalgae. Nonetheless, the primary objective of this study is to examine their sustainable applications, identify potential domains of use, and explore the associated challenges and emerging technologies that enhance their sustainability. The overarching aim is to underscore the contributions of macroalgae to multiple SDGs.

Macroalgae (seaweeds) play a significant role in advancing multiple Sustainable Development Goals (SDGs) by offering promising solutions in areas such as food security, climate change mitigation, sustainable clean energy, and agriculture. Their ecological contribution to marine ecosystems, alongside their socio-economic benefits through job creation and support for local economies, underscores their sustainability potential. Table 1 outlines the specific SDGs supported by macroalgae and highlights the common challenges associated with their cultivation and utilisation. While potential solutions are discussed in detail in the subsequent section, this part focuses on outlining some of the key barriers to their sustainable development.

Table 1. Macroalgae sustainability in support of relevant Sustainable Development Goals and common challenges in their sustainability.

<table>
<tr><th>SDGs</th><th>How do they support relevant SDGs?</th><th>Challenges</th></tr>
<tr><td>2</td><td>Consumed as sea vegetables for direct human consumption, processed and functional food.</td><td rowspan="11">Making seaweed products accessible, appealing, and cheap to billions of people.

Absence of cost-efficient methods for production.

Scarcity of technological development and scientific research.

Contributing to eutrophication, spreading of non-native species, disease, parasites.

Loss of biodiversity.</td></tr>
<tr><td>3</td><td>Controlling cholesterol level and blood sugar, weight reduction, anti-obesity impact, and improvement of cardiac and intestinal health.</td></tr>
<tr><td>6</td><td>Renewable agents for bioremediation
Removing phosphorus and nitrogen from water by absorbing them.
Regulating harmful algal blooms.
Mitigating eutrophication and acidification.
Lacking the requirement of industrial fertilizers.</td></tr>
<tr><td>7</td><td>Source of third-generation bio-fuel production.
Ability to replace conventional biodiesel fuel.</td></tr>
<tr><td>8, 11, 16</td><td>Not only creating new markets and jobs but also supporting local coastal economies.
Opportunities in agriculture, food, alginate industry, cosmetics and health.
Reduced urban waste.</td></tr>
<tr><td>9, 12</td><td>Using seaweed in architecture as a wood replacement.
Innovations such as seaweed-based lipid powder, flour and hydrocolloids.
Reducing land usage and providing renewable resources.
Sustainable packaging alternatives that cut plastic waste.</td></tr>
<tr><td>13</td><td>Mitigating climate change by lowering atmospheric CO_2 levels.
Contributing to the carbon cycle and carbon sequestration.
Recycling of seaweed.</td></tr>
<tr><td>14</td><td>Providing habitat for marine species and supporting marine biodiversity.</td></tr>
<tr><td>15</td><td>Mitigating deforestation and balancing sea–land resource use.</td></tr>
<tr><td>17</td><td>Partnerships among government, private sector, civil society and nations.
Integration of experiential and scientific knowledge.
Need for national and international regulation.</td></tr>
<tr><td>1, 4, 5, 10</td><td>Training youth on environmental, technological and economic issues needed for new markets.
Promoting women’s employment through training and economic opportunities.</td></tr>
</table>

The sustainability of seaweed cultivation faces several overarching challenges, including the need for cost-effective practices, enhanced technological innovation, expanded scientific research, greater collaboration, and the formulation of coherent policy frameworks. Seaweed holds significant potential for supporting various Sustainable Development Goals (SDGs), and its large-scale cultivation is increasingly viewed as a critical pathway toward achieving these objectives. Nonetheless, the primary stages of seaweed production—namely cultivation and harvesting—pose considerable technical and economic obstacles that hinder broader implementation.

Cultivation and harvesting are particularly capital-intensive processes, involving substantial expenditures related to infrastructure, monitoring systems (including Monitoring, Reporting, and Verification, or MRV), and labour. When additional costs associated with downstream applications are factored in, the overall expense often renders seaweed-based products inaccessible to many investors, consumers, and markets. This financial barrier stands in contrast to the broad ambitions of the SDGs, which advocate for an environmentally resilient and socially inclusive future, aiming to mitigate marine and atmospheric pollution, decelerate climate change, safeguard biodiversity, reduce hunger, and address inequality and poverty within an equitable and sustainable framework.

Improper or mismanaged cultivation and harvesting practices can, however, produce adverse ecological consequences. For instance, seaweed absorbs various substances from its surrounding environment—such as heavy metals, pesticides, and excess nutrients (e.g., phosphorus and nitrogen)—which are effectively removed from the ecosystem upon harvesting. Yet, incorrect harvesting techniques may disturb marine ecosystems, exacerbating issues such as eutrophication, acidification, and imbalances in the carbon cycle. According to the GRASS Report (2021) by the Latvian Institute of Aquatic Ecology, the physical configuration of cultivation systems can alter underwater light dynamics, producing shading effects that disrupt photosynthetic activity and local biodiversity. In shallow waters, seaweed farms may compete with native species for sunlight and nutrients, potentially disadvantaging other organisms. Additionally, in the absence of effective monitoring technologies, seaweed biomass may decompose in situ, leading to oxygen depletion. Compounding these concerns, the marine environment limits the feasibility of chemical intervention; hence, the spread of diseases and parasites in seaweed farms remains a critical threat, as conventional pesticide use is unviable.

Consequently, the shading effect, biomass decomposition, and uncontrolled biological contamination can collectively contribute to biodiversity loss and ecosystem degradation. To address these risks, seaweed aquaculture must be supported by continuous environmental monitoring, rigorous scientific research, and the advancement of cultivation and harvesting technologies tailored to ecological sustainability and economic feasibility.

2. Proposed Solutions

Seaweed holds promise across a wide range of applications, contributing significantly to a more sustainable future. It presents viable solutions for enhancing water quality and addressing major global challenges such as climate change, reliance on fossil fuels, deforestation, and poverty. This section explores these sustainability dimensions in detail, outlining the specific roles seaweed can play and the mechanisms through which such contributions may be realised.

2.1. Climate Change

Today, the Earth's climate is changing at an unprecedented rate, largely due to anthropogenic activities such as fossil fuel combustion, industrial processes, deforestation, and urbanisation. The resultant global warming is primarily driven by the greenhouse effect, a phenomenon wherein greenhouse gases trap heat within the atmosphere. Among these gases, carbon dioxide (CO_2) and methane (CH_4) are particularly influential. Consequently, the carbon cycle plays a critical role in determining atmospheric CO_2 concentrations.

To meet the objectives of the Paris Agreement—specifically, limiting global warming to below 2°C by 2030—it is necessary to reduce CO_2 emissions substantially. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, this would require cutting emissions by approximately 52–60 $GtCO_2$ (1 $GtCO_2$ = one billion tonnes of carbon dioxide). Although the more ambitious target is to restrict warming to 1.52°C C, this scenario appears increasingly implausible under current global trajectories.

The IPCC underscores the importance of carbon dioxide removal (CDR) to achieve either net-zero or net-negative CO_2 emissions, where the amount of CO_2 released is balanced or exceeded by the quantity removed from the atmosphere. In this context, seaweed can contribute significantly by regulating atmospheric CO_2 levels. As primary producers, seaweeds engage in photosynthesis, absorbing CO_2 and sunlight to synthesise organic compounds—namely particulate organic carbon (POC) and dissolved organic carbon (DOC)—thus facilitating carbon sequestration, the long-term storage (typically over 100 years) of atmospheric CO_2 in natural reservoirs (Hurd et al., 2023).

During growth, seaweeds sequester carbon within their biomass. Harvesting these organisms can effectively remove CO_2 from the atmosphere, given that seaweed draws carbon originally from atmospheric CO_2 diffused into marine environments. This diffusion is driven by concentration gradients and occurs through surface waters such as rivers and lakes, as CO_2 is soluble in water. Subsequently, this CO_2 is utilised in photosynthesis to generate organic carbon (Hurd et al., 2023; Hurd et al., 2022).

POC consists of small particles and larger organic matter, including detritus and detached thalli, such as blades, holdfasts, and stipes. While some POC serves as food for marine organisms, the rest sinks to the ocean floor, contributing to long-term carbon storage within deep-sea sediments. DOC, by contrast, encompasses dissolved organic compounds; portions of this carbon are consumed by microbes, while others are respired into dissolved inorganic carbon (DIC), facilitating short-term carbon cycling (Egea et al., 2023; Hurd et al., 2023).

Bicarbonate (HCO_3^-), the predominant form of DIC in seawater, plays a central role in maintaining oceanic pH and is utilised by marine organisms for calcification. Upon their death, the carbon embedded in their shells or skeletons is deposited in deep-sea sediments, akin to the sequestration pathway of POC.

In sum, the carbon equilibrium between the ocean and atmosphere involves intricate physical, chemical, and biological processes. While carbon stored in seaweed biomass typically persists for years to decades, carbon sequestered in marine sediments can remain immobilised for millennia, consistent with the principles of blue carbon (Bach et al., 2023; Hurd et al., 2023). Seaweed's capacity to absorb and store carbon thus constitutes a meaningful contribution to climate change mitigation. This application supports SDG 13 (Climate Action) and indirectly contributes to SDG 14 (Life Below Water) and SDG 15 (Life on Land) by strengthening both marine and terrestrial ecosystems.

2.2. Fossil Fuel

Over the last decades, the use of fossil fuels has intensified due to rapid urbanisation and industrialisation, resulting in air pollution, an enhanced greenhouse effect, and global warming. According to the IPCC 2023 Synthesis Report, the combustion of fossil fuels, along with unequal and unsustainable energy and land use, constitutes the primary driver of the observed global warming of 1.1 °C above pre-industrial levels. This highlights the pressing need for renewable energy sources to mitigate climate change, reduce air pollution, and advance sustainability.

Biofuel derived from renewable sources, such as algae, represents a viable alternative to conventional fossil fuels. Biofuels are generally categorised into three types: first-generation fuels derived from food crops; second-generation fuels obtained from non-food crops and waste materials; and third-generation fuels, which are produced from marine resources such as seaweeds and cyanobacteria. The latter offer higher yields and require fewer inputs (Kumar et al., 2021). Kumar et al. (2021) provide a comprehensive overview of biofuel production from macroalgae, outlining a number of complex processes. This paper introduces the basic principles of these processes to ensure accessibility, as the full technical details demand an advanced understanding of biology and chemistry.

Macroalgae feedstocks can be utilised to produce both biodiesel and bioethanol (Kumar et al., 2021; Osman et al., 2020). As shown in Figure 1, biodiesel is generated via transesterification, in which the lipids extracted from dried algal biomass react with an alcohol to yield fatty acid methyl esters. The residual biomass is subsequently fermented to produce bioethanol. Biodiesel serves as a renewable substitute for conventional diesel fuel, while bioethanol, an alcohol derived from algal biomass, functions as a fuel additive to reduce reliance on fossil fuels (Osman et al., 2020; Kumar et al., 2021).

In summary, the use of macroalgae-based biofuels in the energy sector contributes to climate change mitigation and air quality improvement. This solution primarily supports SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 12 (Responsible Consumption and Production), while also indirectly contributing to SDG 14 (Life Below Water).

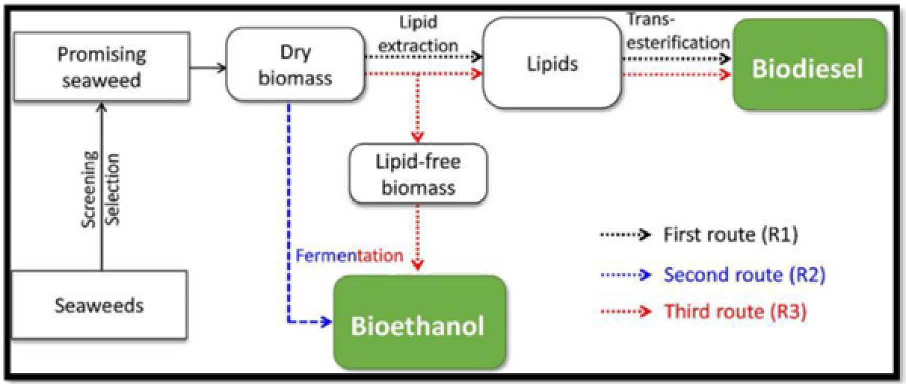

Figure 1. The processes of biodiesel and bioethanol were retrieved from Osman et al. (2020)

2.3. Water Quality

The increasing use of chemicals and plastic, driven by technological advancement, constitutes a major source of water pollution. Seaweeds can mitigate this problem by replacing harmful materials with eco-friendly, macroalgae-derived substances. For example, Marine Macroalgae Waste (MMW) can be used to produce biofertilisers, thereby reducing reliance on chemical fertilisers (Pardilho et al., 2023). During growth, seaweeds can absorb hazardous substances from their surroundings, including heavy metals, nitrogen, and phosphorus. This capability is referred to as bioremediation.

Excess nitrogen and phosphorus in marine environments are the primary causes of eutrophication—a process in which water bodies become overly enriched with nutrients (Jiang et al., 2020). Such nutrient overloads can stimulate harmful algal blooms, such as the mucilage event observed in the Marmara Sea in 2021, and can result in hypoxia by depleting dissolved oxygen levels. A dense algal population can block sunlight from penetrating deeper ocean layers, exacerbating ecological imbalances. Through bioremediation, seaweeds can attenuate local eutrophication and enhance water quality by regulating harmful algal blooms (Jiang et al., 2020; Sultana et al., 2023; GRASS 2021). When harvested, seaweeds containing absorbed pollutants also help remove these substances from aquatic ecosystems.

Harvested seaweed or MMW can subsequently be used as biofertilisers due to their beneficial chemical composition. Seaweeds are rich in organic matter, including amino acids and proteins, which can be directly assimilated by plants, as well as inorganic nutrients such as calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb) (Pardilho et al., 2023). These minerals support plant growth and development; however, certain heavy metals (e.g., Cd, Cr, Cu, Pb, Ni) can be detrimental to soil and plant health, necessitating chemical evaluation prior to application.

In addition, seaweeds possess high fibre content, including polysaccharides such as alginates, which enhance soil water retention (Pereira, L., and Costas, J., 2020). Pardilho et al. (2023) note that the use of MMW as solid organic fertilisers and soil conditioners is a traditional practice in coastal areas. Although this method has largely been replaced by synthetic fertilisers due to the high cost of MMW utilisation, the authors advocate for a return to traditional approaches. Their study on two food crops—kale (a leafy vegetable) and parsnip (a root vegetable)—demonstrates that MMW-derived liquid and solid fertilisers, especially the liquid extracts, significantly improve seed germination and seedling growth.

In addition to chemical pollution, plastic waste represents another major threat to marine environments. Approximately 70–80% of marine plastic pollution originates from terrestrial sources, primarily via rainwater runoff, while the remaining 20–30% is attributed to aquaculture and fishing activities (e.g., discarded nets and gear) (Schmidtchen et al., 2021). The United Nations Environment Programme (UNEP) report, *From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution*, estimates that around 11 million metric tonnes of plastic currently enter the ocean annually, a figure projected to triple by 2040 without intervention. Seaweed-based polymers present a sustainable alternative. Schmidtchen et al. (2021) affirm the viability of producing fully algae-based packaging materials from seaweed polymers, offering an eco-friendly substitute for conventional plastic.

In summary, seaweed contributes meaningfully to improving water quality, treating wastewater, and reducing plastic pollution. These roles support the fulfilment of SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water).

2.4. Deforestation

Seaweed is a marine organism; therefore, producing algae for feed and food can significantly reduce the demand for arable land (Bourgougnon et al., 2021). The production of livestock feed, especially soybeans, plays a substantial role in deforestation, as large areas of forests are cleared to cultivate such crops. For instance, extensive regions of the Amazon rainforest in South America have been deforested to grow feed crops for animal husbandry (Song et al., 2021). Marine macroalgae waste (MMW) can serve as an alternative feed source, thereby decreasing the demand for conventional crops. In addition to its application in animal feed, seaweed can also be consumed directly by humans. Owing to their rich nutritional profile—characterised by high protein, low lipid content, carbohydrates, vitamins, and minerals—seaweeds offer a low-calorie yet nutrient-dense food source (Bourgougnon et al., 2021). Consequently, they have the potential to address both obesity and food insecurity, in line with SDG 3 (Good Health and Well-being) and SDG 2 (Zero Hunger). Their high fibre content and low energy density can enhance satiety, making them effective components of a balanced diet aimed at weight management (Sultana et al., 2023).

Food shortages are expected to intensify in the coming decades, with projections indicating a need to increase global food production by 50–70% by 2050. In this context, seaweed emerges as a promising sustainable food resource for direct human consumption, processed food products, and functional foods (Sultana et al., 2023). In the Asia-Pacific region, seaweed is already integrated into diets in forms such as salads, snacks, desserts, side dishes, and traditional seaweed-based items like Korean *Wakame* and Japanese *Nori* or *Purple Laver*. Their incorporation into processed foods not only enhances nutritional quality but also supports the development of novel, environmentally sustainable food products. Additionally, bioactive compounds in seaweeds contribute functional properties that may offer health-promoting benefits (Sultana et al., 2023).

Moreover, in the context of reducing deforestation, seaweed fibres can be utilised as an eco-friendly substitute for wood in the production of Wood-Plastic Composites (WPCs). These composites—comprising wood fibres and thermoplastics—exhibit high dimensional stability, low weight, long durability, and low maintenance requirements. Integrating seaweed fibres into such composites can enhance their mechanical properties, offering sustainable alternatives to conventional wood-based materials (Vijayasekaran et al., 2023).

In summary, the diverse applications of seaweed—including reducing land use for livestock feed, offering a sustainable food source for human consumption, and replacing wood in composite materials—are aligned with SDG 15 (Life on Land), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), and SDG 9 (Industry, Innovation and Infrastructure).

2.5. Poverty

According to *The Sustainable Development Goals Report 2023*, approximately 575 million people—nearly 7% of the global population—are projected to remain in extreme poverty by 2030. Poverty is a multidimensional concept encompassing hunger, inequality, unemployment, and limited access to education. Addressing these interconnected issues is essential for the eradication of poverty. Seaweed farming and the advancement of seaweed-derived products, as previously discussed, offer a promising pathway toward this objective.

By ensuring a sustainable and nutritious food supply, seaweed-based initiatives directly contribute to the fight against hunger. Simultaneously, the cultivation and processing of seaweed generate employment opportunities, thereby fostering local economic development. This form of economic empowerment also plays a crucial role in reducing social inequality by providing individuals with access to dignified work and income-generating activities.

Notably, seaweed cultivation projects in regions such as Tanzania and India have demonstrated a strong commitment to inclusivity, particularly through the involvement of women. In Tanzania, women constitute nearly 80% of the seaweed farming workforce, while in coastal India, initiatives actively promote female participation through structured training programmes (Sultana et al., 2023). These efforts not only advance women's economic independence but also contribute to the reduction of gender disparities in traditionally marginalised communities.

In conclusion, seaweed-related initiatives hold significant potential for alleviating poverty by tackling its root causes—hunger, unemployment, inequality, and lack of education. Through the creation of sustainable economic opportunities, empowerment of women, and provision of skill development programmes, these initiatives align with SDG 1 (No Poverty), SDG 2 (Zero

Hunger), SDG 5 (Gender Equality), SDG 10 (Reduced Inequalities), SDG 4 (Quality Education), and SDG 8 (Decent Work and Economic Growth).

3. Discussion and Conclusion

This paper highlights the contribution of macroalgae (seaweed) to sustainability and their potential to address global challenges. As vital marine resources, macroalgae support numerous Sustainable Development Goals (SDGs) by offering sustainable alternatives, particularly in the agriculture, energy, and food sectors, with potential applications in architecture and bioplastics.

Seaweed contributes directly to SDG 13 (Climate Action) and SDG 7 (Affordable and Clean Energy) through its role in carbon sequestration and biofuel production. Its capacity to improve water quality, remediate pollution, and replace plastic with eco-friendly materials supports SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water). Moreover, its nutritional content and role in food security address SDG 2 (Zero Hunger), while its use as an alternative to land-intensive crops and wood aligns with SDG 15 (Life on Land). Seaweed-based activities also support SDG 1 (No Poverty), SDG 5 (Gender Equality), SDG 10 (Reduced Inequalities), SDG 4 (Quality Education), SDG 8 (Decent Work and Economic Growth), and SDG 16 (Peace, Justice and Strong Institutions) by fostering employment, reducing inequality, and empowering marginalised groups. Further, innovations in seaweed-derived products promote SDG 9 (Industry, Innovation and Infrastructure), while their incorporation into circular economy models contributes to SDG 12 (Responsible Consumption and Production) and SDG 11 (Sustainable Cities and Communities). The advancement of seaweed-related initiatives requires multi-level cooperation, as articulated in SDG 17 (Partnerships for the Goals).

Given this potential, the question arises: what actions can be initiated—starting from our campuses to our cities, countries, and globally? Unfortunately, macroalgae cultivation and usage remain uncommon in Türkiye. Nevertheless, the following roadmap is proposed:

At the campus level, academic institutions should initiate extensive research on seaweed cultivation, environmental impact, and sustainable applications. Research should focus on identifying challenges in seaweed farming, optimising cultivation techniques, and quantifying environmental benefits such as carbon sequestration and water purification. In parallel, efforts should explore innovative uses in agriculture, bioenergy, and bioplastics. Interdisciplinary collaboration across biology, chemistry, environmental science, and engineering should be fostered to cultivate a robust academic ecosystem around seaweed innovation. Students and faculty should be actively encouraged to participate in such research efforts, thereby transforming campuses into living laboratories for sustainability.

At the city and national level, governmental bodies should implement policies that ensure ecological protection, ethical harvesting, and the responsible management of seaweed ecosystems. Regulatory frameworks must address overharvesting, marine conservation, and fair labour practices. Furthermore, public–private partnerships among research institutions, industry, and governmental agencies are essential for knowledge exchange and coordinated development. Financial incentives such as grants, subsidies, and tax benefits should be provided to stimulate entrepreneurship and innovation in the seaweed sector. This can catalyse local economic development, employment, and resilience, especially in coastal communities.

At the global level, multinational corporations should invest in sustainable seaweed supply chains and promote seaweed-based innovations. Efforts should be made to harmonise standards for environmental conservation, quality assurance, and ethical practice through collaboration with international organisations. Moreover, international research cooperation is vital to foster the exchange of data, technologies, and methodologies, enhancing global capabilities in sustainable seaweed utilisation.

In conclusion, macroalgae hold substantial promise for advancing global sustainability goals. With strategic research, policy support, and international collaboration, seaweed can become a transformative agent in the pursuit of a more equitable, resilient, and sustainable future.

CRediT Yazar Katkı Beyanı

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Çıkar Çatışması Beyanı

Yazarlar, herhangi bir çıkar çatışması olmadığını beyan etmektedir.

Referanslar

Bach, L. T., Ho, D. T., Boyd, P. W., and Tyka, M. D. (2023). Toward a consensus framework to evaluate air–sea CO_2 equilibration for marine CO_2 removal. *Limnology and Oceanography Letters*, 8, 685–691.

Bourgougnon, N., Burlot, A. S., and Jacquin, A. G. (2021). Algae for global sustainability?. *Advances in botanical research*, 100, 145-212.

Egea, L. G., Infantes, E., and Jiménez-Ramos, R. (2023). Loss of POC and DOC on seagrass sediments by hydrodynamics. *Science of the Total Environment*, 901, 165976.

GRASS Report. (2021). Ecological impact of macroalgae cultivation in the Baltic Sea region. Latvian Institute of Aquatic Ecology. European Union. https://www.submariner-network.eu/

Hurd, C. L., Gattuso, J.-P., and Boyd, P. W. (2023). Air-sea carbon dioxide equilibrium: Will it be possible to use seaweeds for carbon removal offsets? J*ournal of Phycology*, 60(1), 1–11.

Hurd, C. L., Law, C. S., Bach, L. T., Britton, D., Hovenden, M., Paine, E. R., Raven, J. A., Tamsitt, V., and Boyd, P. W. (2022). Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. *Journal of Phycology*, 58(3), 347–363.

IPCC. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

Jiang, Z., Liu, J., Li, S., Chen, Y., Du, P., Zhu, Y., Liao Y, Chen Q, Shou L, Yan X, Zeng J, and Chen, J. (2020). Kelp cultivation effectively improves water quality and regulates the phytoplankton community in a turbid, highly eutrophic bay. *Science of the Total Environment*, 707, 135561.

Kumar, D., Pugazhendi, A., Bajhaiya, A. K., and Gugulothu, P. (2021). Biofuel production from Macroalgae: present scenario and future scope. *Bioengineered*, 12(2), 9216.

Osman, M. E., Abo-Shady, A. M., Elshobary, M. E., Abd El-Ghafar, M. O., and Abomohra, A. E. F. (2020). Screening of seaweeds for sustainable biofuel recovery through sequential biodiesel and bioethanol production. *Environmental Science and Pollution Research*, 27, 32481-32493.

Pardilhó, S., Cotas, J., Pacheco, D., Bahcevandziev, K., Pereira, L., Oliveira, M. B., and Diasi J. M. (2023). Back to the Origins: Potential of Beach-Cast Macroalgae as Biofertilizer. *Waste and Biomass Valorization*, 14, 1097–1111.

Pereira, L., and Cotas, J. (2020). Alginates - A General Overview. IntechOpen.

Schmidtchen, L., Roleda, M. Y., Majschak, J.-P., and Mayser, M. (2021). Processing technologies for solid and flexible packaging materials from macroalgae. *Algal Research*, 61, 102300.

Song, X. P.; Hansen, M. C.; Potapov, P.; Adusei, B.; Pickering, J.; Adami, M.; Lima, A.; Zalles, V.; Stehman, S. V.; Di Bella, C. M.; Conde, M. C.; Copati, E. J.; Fernandes, L. B.; Hernandez-Serna, A., Jantz, S. M.; Pickens, A. H.; Turubanova, S.; Tyukavina, A. (2021). Massive soybean expansion in South America since 2000 and implications for conservation. *Nature Sustainability*, 4(9), 784-792.

Sultana, F., Wahab, M. A., Nahiduzzaman, M., Mohiuddin, M., Iqbal, M. Z., Shakil, A., Mamun, A., Khan, M. S. R., Wong, L., and Asaduzzaman, M. (2023). Seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment: A review. *Aquaculture and Fisheries*, 8(5), 463-480.

UNEP Report. (2021). From Pollution to Solution: A global assessment of marine litter and plastic pollution. UNEP - UN Environment Programme. https://unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution.

Vijayasekaran, G., Kamal, M., Gopi, M., Nanthakumar, S., and Girimurugan, R. (2023). Enhancement of natural fiber-reinforced plastics by polyester and seaweed waste fibers.

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Makroalglerin (deniz yosunlarının) sürdürülebilirliğe katkısı

Genişletilmiş Özet

Giriş

Bu çalışma, makroalglerin (deniz yosunlarının) birden çok Sürdürülebilir Kalkınma Amacı'na (SKA) eş zamanlı katkı potansiyelini değerlendirmektedir. Araştırmanın temel hedefi, makroalg temelli ürün ve hizmetlerin iklim değişikliğiyle mücadele (SKA 13), temiz ve erişilebilir enerji (SKA 7), gıda güvenliği (SKA 2), su kalitesinin iyileştirilmesi (SKA 6), sorumlu üretim-tüketim (SKA 12) ile kara ve su ekosistemlerinin korunması (SKA 14 ve 15) başta olmak üzere çok sayıda amaca nasıl hizmet edebileceğini ortaya koymaktır.

Yöntem

Çalışma kapsamlı bir literatür taraması, sektör raporları ve güncel uygulama örneklerinden yararlanarak makroalglerin tarım, enerji, gıda, su arıtımı, biyo-malzeme ve istihdam alanlarındaki sürdürülebilirlik katkılarını sentezlemiştir. Ek olarak, yetiştiricilik (kültivasyon) ve hasat süreçlerinde karşılaşılan maliyet, teknoloji, izleme-raporlama-doğrulama (MRV) altyapısı ve politika boşlukları analiz edilmiştir.

Bulgular

İklim Eylemi: Makroalgler, fotosentez yoluyla atmosferik CO_2'yi biyokütlede ve derin deniz tortullarında depolayarak mavi karbon havuzlarını güçlendirmektedir.

Temiz Enerji: Transesterifikasyon ve fermantasyon süreçleriyle biyodizel ve biyoetanol üretimi mümkündür; üçüncü nesil biyo-yakıtlar fosil yakıtlara rekabetçi bir alternatiftir.

Su Kalitesi ve Döngüsel Ekonomi: Makroalgler azot-fosfor giderimi sağlayarak ötrofikasyonu azaltır; hasat sonrası atık biyokütle biyo-gübre veya biyoplastik hammaddesi olarak değerlendirilebilir.

Gıda ve Beslenme: Yüksek protein, düşük yağ ve zengin mikro-besin içeriği sayesinde obeziteyle mücadele ve gıda arz güvenliğine katkıda bulunur.

Sosyo-ekonomik Etki: Özellikle kıyı topluluklarında kadın istihdamını artıran deniz yosunu çiftlikleri, yerel ekonomi ve yoksulluğun azaltılmasına (SKA 1, 5, 8, 10) destek olur.

Sonuç ve Öneriler

Makroalg temelli çözümler, iklim krizinin hafifletilmesinden döngüsel ekonomiye geçişe kadar geniş bir yelpazede sürdürülebilir kalkınmayı hızlandırma potansiyeline sahiptir. Ancak maliyet etkin teknolojiler, bilim-sanayi iş birliği ve ulusal/uluslararası düzenleyici çerçevelerin güçlendirilmesi gereklidir. Çalışma, üniversite kampüslerinden başlayarak ulusal ve küresel ölçekte Ar-Ge teşvikleri, finansal destek mekanizmaları ve standartlaştırılmış çevresel izleme sistemlerinin oluşturulmasını önermektedir. Böylece makroalgler, daha adil, dirençli ve sürdürülebilir bir geleceğe geçişte kilit bir biyolojik kaynak olarak değerlendirilebilecektir.