EXPLOITATION OF OVERRUN MACROALGAE AS MODEL TO LEAD THE CIRCULAR ECONOMY TRANSITION AND THE BIOECONOMY GROWTH

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INTRODUCTION by Francesco Petracchini

The circular economy transition represents a unique opportunity. We should approach this complex topic not just as a way to improve our waste management, but mainly as a precious tool to face global environmental challenges of our time, as the global heating, and to reach the Sustainable Development Goals (SDGs), fixed by the United Nations.
Considering the linear production flow, where materials, with high economic value but high supply risk, are extracted from the earth, processed into products, and then trashed as waste, the waste management can be considered as a crossing issue, involving every phase of the productive cycle. "More than 50% of greenhouse gas emissions are related to materials management, making more efficient use of materials is a sound greenhouse gas mitigation strategy" (E.E.A.,2019). By reducing waste, closing material loops, and making products that can be reused, remanufactured or recycled, the huge impacts of materials extraction and processing could be substantially reduced.
The implementation of the circular economy model, especially when addressed to the waste prevention, needs the promotion of the research on biological elements aimed to the evaluation of the effects of introducing biological materials in new advanced production cycles on society, health and economy and the environment as a whole.

In force of these motivations the Institute of Atmospheric Pollution Research (CNR) is strongly involved in the field, also by collaborating with other eminent research institutions.
In 2020, as the Director of the Institute, I subscribed a four-year Operating Agreement with the Department of Biotechnology Chemistry & Pharmacy of the University of Siena (excellence Department 2018-2022), to develop projects aimed to the national bioeconomy growth and inspired by the real circular economy principles and targets.

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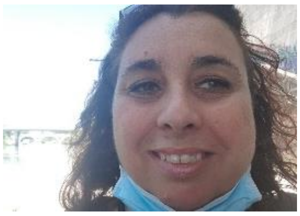

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Chi vuole guardare bene la terra deve tenersi alla distanza necessaria

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EXPLOITATION OF OVERRUN MACROALGAE AS MODEL TO LEAD THE CIRCULAR ECONOMY TRANSITION AND THE BIOECONOMY GROWTH

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ABSTRACT

During the times of a challenging transition from a linear to a circular economy, while many productive processes or systems have to be redesigned to limit losses, waste, and their environmental impacts and, at the same time, to find sustainable and alternative resources to feed its cycle, research activities reveal their crucial role to get new knowledge and new opportunities, especially in the biotechnologies field.
Under the light of the circular economy, looking at the last European legislation on waste, and in force of the outcomings of specific research activities on biowaste, this paper analyzes the potentialities of the exploitation of overrun and infesting seaweeds, now considered as waste, for different uses in various productive cycles. The paper aims to show how the described applications for overrun algae are fully corresponding to the circular economy principles and the UN's Sustainable Development Goals. The matches are highly remarkable, especially looking at the latest European legislation on waste management. Some specific applications on seaweeds, described in this paper, should be considered further as a model to follow. In the current framework especially looking at the absence of adequate indicators to measure the circularity level related to products and processes, the sharing of a correct approach should be enhanced to maximize results and drive the circular economy transition and the desired simultaneous bioeconomy growth on the right track.

KEYWORDS: circular economy; Sustainable Development Goals; bioeconomy; biotechnologies; seaweeds; electrospinning; waste management.

1. *INTRODUCTION*

There is a deep connection between every field of human action and the environmental challenges of the twenty-first century. Thus, it's becoming more and more difficult to observe and globally evaluate the real environmental benefits and impacts originated by specific actions, even if these are taking life from a pure green purpose.

Observing the linear economy pattern, which steered industrial development during the last century, materials are extracted from the earth, processed, made into products, and then trashed as waste. It's admissible to consider waste management as a crossing issue, involving every phase of the productive cycle. Therefore, the adoption of a new economic model based on circularity should not be considered just as a way to improve waste management, but also as a precious tool to change the global productive system and to reach the Sustainable Development Goals (SDGs), fixed by the United Nations. Waste always represents a squandering of resources, and the circular economy legislation-pack, released by the European Commission, is the proof of the fundamental relevance of the waste issue and of its existing interactions. By reducing waste, closing material loops, and making products that can be reused, remanufactured, or recycled, the huge impacts of materials extraction and processing could be substantially reduced. In this contest, funding and implementing research on the use of biological elements in the production cycles get a basic relevance to evaluate both the processes' effectiveness and its externalities on environment, society, health and economy. This is particularly true when these biological elements are introduced to replace traditional and raw materials.

While governments are catching for a real and global improvement of environmental conditions and welfare levels, the simultaneous growth of circular and bioeconomy is desirable and gets a strategic relevance**,** especially for Europe, as the European Environmental Agency (E.E.A.) hammered down on its last reports on the field *(E.E.A. report n. 8/2018, n. 11/2019).*

In such a framework, algae might represent an extraordinary resource, not only for their natural proprieties but also for the number of applications that deserve to be explored as a disruptive innovative economic model with zero-waste. More in detail, macroalgae, living in a wide variety of marine and freshwater ecosystems, are proved to offer significant economic and environmental advantages over terrestrial biomass, as rapid growth rate and photosynthetic efficiency no competition for agricultural land, cultivation without needing fertilization and unique components. Algae are photosynthetic aquatic organisms and need three major components for growth, including sunlight, water, and carbon source. They possess plant-like structural features that grow to large size (50 cm up to 60 m in length), comprising a blade or lamina, the stipe, and holdfast for anchoring the entire structure to hard substrates in aqueous environments. Often the separation from the substratum brings to the surfacing on the waterline. Their life cycles are complex and diverse; therefore, macro-algae can be classified by their reproduction cycle, as well different pigmentation (red "*Rhodophyta*", brown "*Phaeophyta"* and green algae "*Chlorophyta*").

As reported above, algae might represent an extraordinary resource; however, many innovative applications are still in their infancy while others are well known. Among these, applications in agri-food, cosmetics, textile, packaging, wastewater treatment, building, and construction sectors show innovative approaches and huge potential as model generating resource productivity improvements.

In *chapter n. 2,* the authors provide a brief explanation of the reasons why the growth of the bioeconomy should be combined with the auspicated transition to a circular economy, underling the potential synergies that could be created through this combination.

Chapter n. 3 of this paper is oriented to frame and highlight how sustainable exploitation of seaweeds can help to reach targets fixed by the European legislation pack on circular economy and, moreover, the United Nations Sustainable Development Goals (SDGs).

In *chapter n. 4,* the authors report a concise framework related to the main sustainable and experienced practices about the algae's exploitation.

In *chapter n. 5,* finally, some specific and innovative applications, inspired by the will to realize a circular use of overrun seaweeds/macro-algae, actually considered as waste, are illustrated as contributing to the rethinking of many various aspects production and consumption chain supporting closed-loop cycle. More in detail, *paragraph §5.1* focuses on some algae's exploitation for the extraction of bioactive elements to be introduced in the productive cycles. These activities are subject to the research activities carry on by the Department for Biotechnologies, Chemistry, and Pharmacy of the University of Siena. *Paragraph §5.2* reports some of the most recent studies that confirm that the *electrospinning* technology is a suitable way to transform algal derivatives into advanced nanostructured biomaterials to be introduced within identified productive cycles (in agriculture, food, sensors, environment, energy, etc.), a research's field where the Institute of Atmospheric Pollution Research of the Italian National Council of Research is active and strongly involved.

The descending and innovative applications for algae, coming out from these research's lines *(chapter n. 5),* strive for the highest targets pointed out by the circular economy pattern and reveal their main strength, fully matching the incredible number of interconnections generated by the social, economic and environmental challenges of our times.

2. *CIRCULAR AND BIO-ECONOMY, EXISTING AND AUSPICATED SYNERGIES*

Circular economy and bioeconomy existing synergies are often remarked by the European authorities, for instance in the European Environment Agency (E.E.A.) report that carefully considers the trade-off of the increased circularity to better respond to people needs for food, feed, biomaterials, and bioenergy resources and the mitigation of the related environmental impacts, for instance in terms of reduced greenhouse gas emission levels; reduced input of natural resources; reduced valuable materials losses; increased shares of renewable and recyclable resources; increased durability of products. As a matter of fact, waste and pollution are the results of the inefficient way business models are designed; through a much greater focus on the natural systems, it is possible to promote intervention to shift to a business system where there are endless possibilities to create a thriving economy *(Ellen Mac Arthur Foundation, 2019; Esposito et al., 2018).*

The deep connection between circular and bioeconomy is soon clear, also looking at the two related definitions, respectively taken by the Ellen McArthur Foundation (*Towards a circular economy: business rationale for an accelerated transition, 2015)* and by the European Commission *(Innovating for Sustainable Growth: A Bioeconomy for Europe, 2012).*

Moreover, it is possible to find clear links between the *2018 Circular Economy Policy Package* and the *2012 Bioeconomy Strategy,* updated in 2018, which identified priority areas of intervention such as food waste, biomass and bio-based products.

In the *European Bioeconomy Stakeholders Manifesto* the concept of circularity was specifically embraced as the way to ensure the growth of the sector. The Manifesto endorses the convenience of a simultaneous growth of bio and circular economy to take the advantage of the several potential synergies and to ensure a sustainable use of resources in both systems *(European Bioeconomy Stakeholders Panel, 2017).*

The natural systems cascade endlessly, without any generation of waste, for its capacity of to self-regulate, pursuing autopoiesis (*Pauli, 2017*).

Despite all these eminent references, currently, bioeconomy and circular economy are loosely associated, even though there is room for strategic synergies in practices and policies, collaboration among the actors throughout the value chain has to be certainly developed and substantially improved *(EEA, 2018).*

The sector of the production of bioplastics and bio-composites is anyway rapidly evolving in the light of bioeconomy. Innovation is mainly focused on the shift from fossil resources. Particular attention is devoted to high-volume applications, including carrier bags and single-use packaging, especially since introducing of the European legislation to minimize the single-use plastics. Besides, research and development efforts are increasingly gearing towards the production of bioplastics from non-edible biomass and bio-waste.

3. *HOW SEAWEEDS EXPLOITATION CAN HELP ACHIEVING THE U.N.-S.D.Gs. AND E.U.'S CIRCULARITY TARGETS*

To innovate deeply the bioeconomy, fully matching the circular economy principles, more than some efforts should be focused on a shift to alternative sources of biomass. Aquatic sources of biomass could be especially helpful because they can be mainly used without the need for additional land for production, preventing problems connected to the competition with the agri-food industry. Looking at soil availability and coastline extension, circular potentialities of aquatic resources could be, for morphological reasons, more and more interesting for a country like Italy. To preserve land and environment and to reach the fixed targets to mitigate the climate change, in a developed country like Italy, artificial surfaces should be considered as something to prevent in the future, while natural ecosystems should be considered as holy places to preserve and enlarge.

In the European Union, Italy is the richest country for biodiversity and the value of agricultural activities. Bioeconomy development and green forest management have a key role in fighting against climate change and increasing the value of the natural national capital. The latest national agricultural indicator trends show the upswing of the general economic value of the primary sector, especially leaded by biological and "*Protected Geographical Indication*" productions. It is important to underline the corresponding growth of secondary and supporting activities behind the national forestry and agricultural sectors. These sectors seem mature enough to enlarge and enforce their diversification activities, showing a large extra-agricultural dimension potentiality.

Looking at the 2019 ISPRA report on land use in Italy, 51 km^2 of land was consumed in 2018 by an average national consumption of about 14 hectares by day. Such land consumption is due to the growth of artificial areas during the last year, which affects the environment by a double perspective, reducing land availability for natural areas and enlarging urban artificial areas. The growth of artificial areas, especially inside cities, brings directly to urban heat islands' formation. Normally it is possible to observe, during the summer, a temperature difference of 2 °C/5 °C between suburban rural areas and city with a high density of built-up areas. Thus, the adoption of responsible land use choices shows its pivotal relevance to contrast climate change and its consequences. The use of land to enlarge artificial areas directly implicates a local temperature increase and, indirectly, a soil availability limitation for reforestation Simultaneously, trees are the perfect natural tool to restore air quality and bring CO_2 global level to average. In *Table n. 1*, percent data on land use by main European countries in 2018 are reported.

Artificial surfaces	
Netherlands	13,74
Germany	9,37
U.K.	8,72
Denmark	8,24
Poland	6,21
France	6,00
Italy	**5,56**
Portugal	4,07
Spain	2,70
Sweden	1,53
Finland	1,41

Agricultural areas	
Denmark	72,50
Netherlands	59,67
France	58,65
Poland	58,65
Germany	56,51
U.K.	54,97
Italy	**51,81**
Spain	47,87
Portugal	47,44
Sweden	8,83
Finland	8,30

Forest and semi natural areas	
Sweden	74,65
Finland	74,53
Spain	48,53
Portugal	46,60
Italy	**41,31**
France	33,75
Poland	33,03
Germany	31,30
U.K.	24,29
Denmark	13,90
Netherlands	10,76

Wetlands	
U.K.	10,50
Netherlands	7,18
Sweden	6,69
Finland	6,32
Denmark	3,21
Germany	1,22
France	0,70
Portugal	0,38
Poland	0,36
Italy	**0,23**
Spain	0,22

Water bodies	
Finland	9,45
Netherlands	8,65
Sweden	8,29
Denmark	2,15
Poland	1,76
Germany	1,60
U.K.	1,53
Portugal	1,51
Italy	**1,09**
France	0,9
Spain	0,68

Table n. 1 -Land use data. Source: author elaboration on data by EEA (https://www.eea.europa.eu/)

3.1 The long way to a transition to a circular economy and to the achievement of the SDGs

Looking at progress in the implementing transition to a circular economic model in each Member State (UE 28), it is important to remark a good placement for Italy, always ranked in the first three positions, as shown by the main circularity indicators implemented by the European Commission, EUROSTAT and OECD *(Table n. 2).*
However, as emphasized by several authors *(Elia et al., 2017; Di Maio et al.; 2017; Cayzer et al., 2017; Gisellini et al., 2016; Moraga et al., 2019)*, effective indicators that specifically focus on the transition from a linear economy to a circular economy are still under discussion.

Circularity indicator	*Italian placement in EU28*
GDP/DMC (resources productivity) = 3,5 €/kg *(where GDP is the gross domestic product and DMC is the domestic materials consumption)*	Italy gets a second place behind the UK, the average value for EU28 is 2,2
DMC (domestic materials consumption pro capite) = 8,3 t/person *(where DMC is the domestic materials consumption)*	Italy gets the first place, the average value for EU28 is 13,2
CMU (circular materials use % rate) = U/DMC=17,1% *(where U is the amount of secondary raw material and DMC is the domestic materials consumption)*	Italy gets the third place behind France and the UK, the average value for EU28 is 11,7 %

Table n. 2 -Circularity indicator trends, Italian performances in EU28. Source: author elaboration on data by Ronchi (2019) "Relazione sullo stato della green economy 2019"

If circular indicators prove a prominent position for Italy, as shown above, by other data, a big lack arises from eco-innovation.
Indeed, Italy, looking at the overall picture performance in 2017 and in the EU28 contest, gets only a 22° position for public spending on *Research and Development* (R&D). Comparing to the top European economies, Italy reaches, moreover, a low amount of patent requests for recycling and secondary raw materials. In the described national contest, an eco-innovation overlook represents a huge limit. This lack is even more dangerous, while R&D activities are recommended by mutual consensus as traction forces to lead and boost the auspicated transition to the circular economic model. Funding R&D public activities on circular bioeconomy ensures a deeper analysis of mentioned interactions, with both climate change mitigation/adaptation policies and SDGs achievement. SDGs are 17 specific targets to get within 2030, identified by the United Nations (U.N.) with the approval of the "*Agenda 2030*". The Agenda, approved on the 25th of September 2015, represents a historical step in the development of the whole world. The innovative aspect is on "sustainability", which is not still bordered within the limits of an environmental concept, but it is involved in each dimension of the human development and needs to be evaluated through an integrated vision. With this approach, nations all over the world, have to hold on the way to sustainable development, enabling every distinction between Developed Countries, Developing Countries, and Rising Economies. Thus, through an integrated

process by the U.N., choices to get SDGs in a single country will be next examined to globally evaluate the related results.

Fig. n. 1 - The United Nations Sustainable Development Goals. Source: https://un.org/en/

The U.N. monitor the SDGs achievement every four years, during the O.N.U. General Conference. There was a first check last September. Some interesting output turns from the indicator trends related to the EU and for Italy, as reported in *Table 3.*

SDGs indicators - European Union

Performances (2010-2017)	Goals
Positive trends	3) good health and well-being; 4) quality education; 5) gender equality; 7) affordable and clean energy; 8) inclusive economic growth; 11) sustainable cities; 12) responsible consumption and production; 13) climate change; 14) water life.
Unvaried trends	1) no poverty; 2) zero hunger; 9) industry and infrastructures; 10) reduced inequalities; 16) peace and justice.
Negative trends	15) protect life and land; 17) partnership.

SDGs indicators - Italy

Performances (2010-2017)	Goals
Positive trends	2) zero hunger; 3) good health and well-being; 4) quality education; 5) gender equality; 7) affordable and clean energy; 9) industry and infrastructures; 12) responsible consumption and production; 13) climate change; 17) partnership.
Unvaried trends	10) reduce inequalities;16) peace and justice.
Negative trends	1) no poverty; 8) inclusive economic growth; 11) sustainable cities; 14) water life; 15) protect life and land.

Table n. 3 -SDGs, European and Italian performances. Source: author's elaboration on data by E. Giovannini et al. (2019)

Looking at trends of indicators in the global contest, although four years have passed since the adoption of the Agenda, a considerable distance to the SDGs achievement still arises despite progress. The main and urgent issues are to tackle climate change and related inequalities. Two massive global emergencies are connected to each other, as every target by the Agenda 2030. Climate change is and will be clearly heavier for vulnerable countries, and its side effects are widely going to exacerbate inequalities. A long road has still to be also covered to reduce the word hunger and to protect life and environmental eco-systems. In Europe, positive results are descending from goals n. 3, n. 4, n. 5 n. 7, n. 8, n. 11, n. 12 and n. 13, while values related to goals n. 15 and 17 show negative trends. Europe, overall, seems to preserve its leadership for the global switch to sustainable development.

The European aggregate result hides, anyway, substantial differences between each country. Is possible to observe this, also looking at the indicator trends for Italy. An Italian delay, conflicting with European trends, arises from the observation of indicators n. 8, 11, 14**,** and from the observation of indicators n. 1 and 15 *(look at underlined voices in the chart n. 3).*

3.2 Role and potentialities of specific R&D activities on seaweeds in the transition to a circular economy

To face negative trends, Italy has to be strongly focused on innovations, especially to ensure inclusive economic growth, improve the quality of life in urban areas, protect the seas, marine resources, and coastline. In the Italian national contest, considering the natural capital high value and the present socio-economic condition, bioeconomy and biotechnologies' innovations must play a key role.

R&D public activities, considering fully and fairly positive and negative externalities for environment and society, represent the only way to evaluate the contribution to the SDGs achievement, coming, for instance, from the introduction of new biological secondary raw materials in the production cycles. R&D activities for the development of circular bioeconomy should be especially focused on a suitable shift to alternative biomass sources. Circular potentialities of aquatic sources of biomass, such as algae, should be especially investigated because of their extraordinary number of green applications, from the bioenergy production to the applications in the feed, textile, cosmetics, nutraceuticals, buildings, and bioremediation fields. In the chart (*chart n. 4*) reported below is possible to observe, for instance, the matches between the key characteristics of a circular economy, extracted by the E.E.A. report n. 2/2016, and the selected and innovative activities for the exploitation of macro-algae/seaweeds, which will be widely illustrated forward in this review (*chapter 5*). The matches are remarkable.

Key characteristics of a circular economy (EEA report 2/2016)	**Infesting macroalgae exploitation**	
	Extraction of bioactive elements for cosmetic industry	**Electrospinning technology to realize nanostructured biomaterials**
Less input and use of natural resources		
• minimised and optimised exploitation of raw materials, while delivering more value from fewer materials	V	V
• reduced import dependence on natural resources	V	V
• efficient use of all natural resources	V	V
• minimised overall energy and water use.	*to evaluate*	*to evaluate*
Increased share of renewable and recyclable resources and energy		
• non-renewable resources replaced with renewable ones within sustainable levels of supply	V	V
• increased share of recyclable and recycled materials that can replace the use of virgin materials	V	V
• closure of material loops	V	V
• sustainably sourced raw materials.	V	V
Reduced emissions		
• reduced emissions throughout the full material cycle through the use of less raw material and sustainable sourcing	V	V
• less pollution through clean material cycles.	V	V
Fewer material losses/residuals		
• build up of waste minimised	V	V
• incineration and landfill limited to a minimum	V	V
• dissipative losses of valuable resources minimised.	V	V
Keeping the value of products, components and materials in the economy		
• extended product lifetime keeping the value of products in use	V	V
• reuse of components	V	V
• value of materials preserved in the economy through high-quality recycling.	V	V

Table n. 4 –Matches between a circular economy key characteristics and selected applications for macroalgae. Source: author's elaboration on report n. 2/2016 by E.E.A.

It is possible to realize some useful evaluations about the circular potentialities of algae applications, also moving this analysis through the milestones on waste management, fixed by the last European legislation pack on waste management.
As noteworthy, European legislation on circular economy *(Dir. n. 849; n. 850; n. 851; n. 852/2018*) heads to the enforcement of the waste management hierarchy, a masterpiece of the environmental legislation to keep the SDGs. The following illustration *(fig. n.2)* shows, referred to the selected applications for macro-algae (in the cosmetic industry and in a different productive cycle by the use of the *electrospinning* technology), the fields of action within the waste management hierarchy:

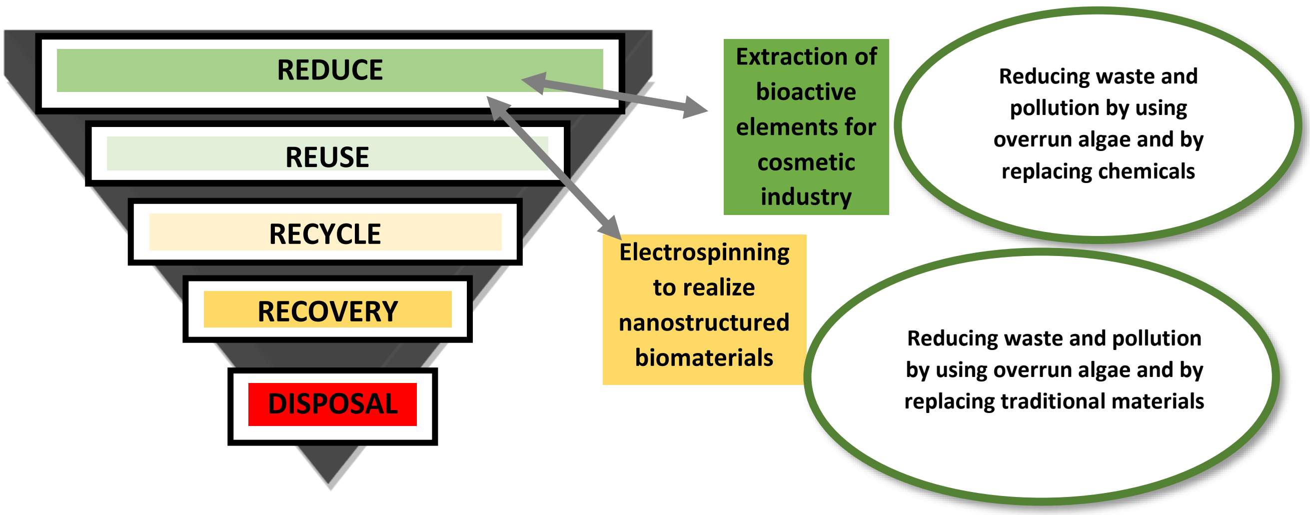

Fig. n. 2 - Collocations of the three selected applications for overrun macroalgae within the European hierarchy for the waste management. Source: author's elaboration on waste management hierarchy by art.4, Dir.2018/851/EU.

Applications based on macro-algae (illustrated in the following *chapter n. 5)* are located at the top of the hierarchy. With such kinds of innovative activities, in each involved sector, replacing traditional components with biological products is executed within the production phase and ensures a reduction of waste all over the consumption phases. Innovations introduced in the production phase allow for the prevention of waste and stimulate conditions to achieve several advantages for the environment and health all over the whole consumption cycle of the considered product (material input; eco-design; production; consumption; waste recycling). If the reduction of waste is the first step to enforce the hierarchy of waste management, prevention represents the best way to get long-term results.
Related to the proposed applications for macro-algae, eco-design in the production phase consents replacing chemicals and environmental pollutants with renewable resources. This is fully agreed with the definition of "eco-design" by the United Nation Environment Programme (UNEP., 2019). From this perspective, applications for macro-algae, especially when these biomasses are considered a problematic waste, may lead to a reduction of waste and ensure a relevant decrease in needs for raw and input materials, energy, and water. In this context, the proposed applications for algae ensure

an extraordinary fullness, considering a large number of connections between waste management and other problematic issues, and providing the surfacing of benefits for health, environment, and economy. The illustration below (*fig. n. 3*) shows how applications for macro-algae, like the selected ones, are considering a larger background (green economy focus) comparing to projects just created to improve waste management (circular economy focus).

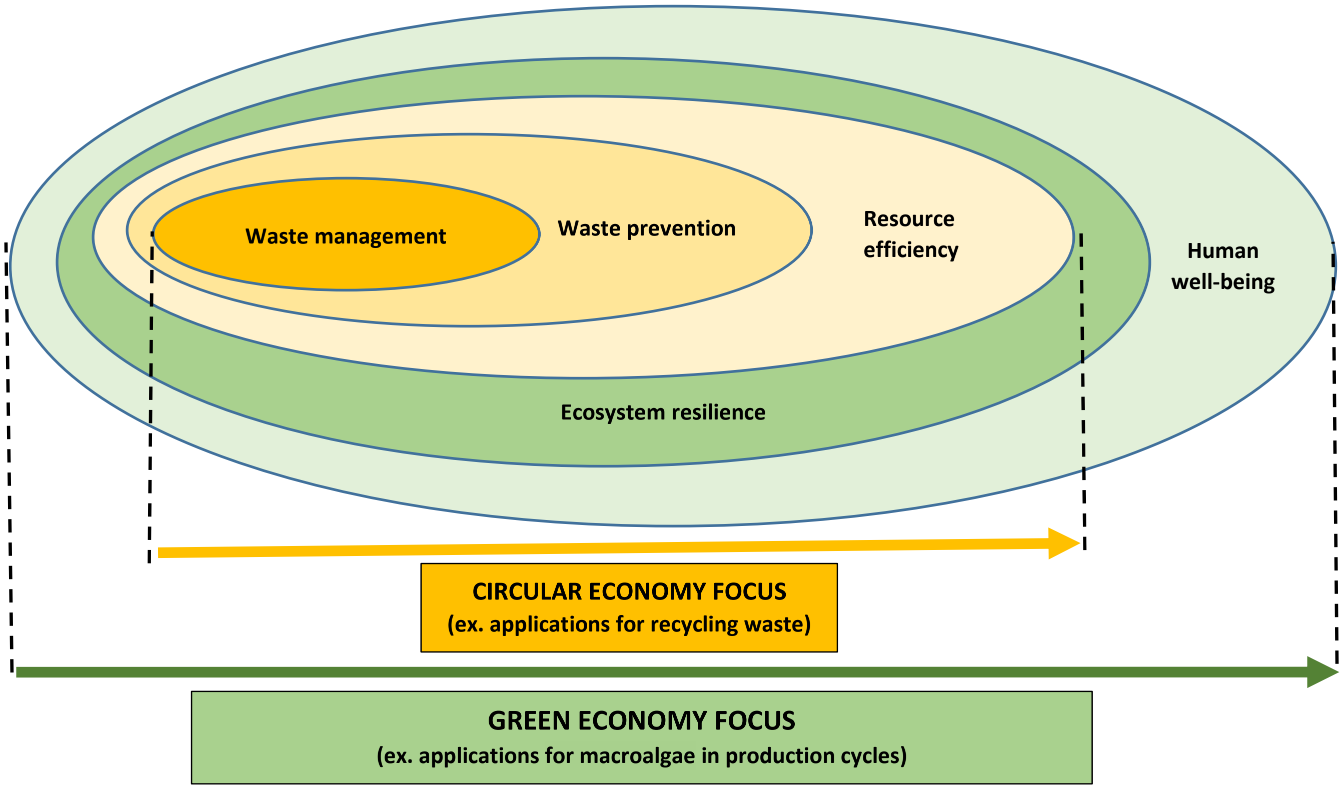

Fig. n. 3 - Focus areas related to circular and green economy projects. Source: author's elaboration on the figure by EEA report n. 2/2016

Analysing the present time of transition towards a new economic model based on circularity the European Commission underlines the fundamental role of research on bioeconomy and the strategic importance of financing projects, which entail the economic financial aspects and all the social and environmental externalities. With this approach to circularity, the algae's exploitation for innovative applications is undoubtedly a precious resource.

Research activities on bioeconomy, especially on seaweeds and aquatic sources of biomass, aimed to real and substantial innovation are in line with the "*cradle to cradle*" concept, inspired by M. Braungart. (Founder of the *EPEA - Environmental Protection Encouragement Agency*, settled in Hamburg since 1987). This "*cradle to cradle*" concept goes further than circular economy focus, and it is strongly based on the belief that we can do something more than minimize our environmental damages. The environmental protection should've considered as something more challenging than simple minimization of impacts. Braungart (1987) endorses innovations aimed to generate positive effects on the environment. The "*cradle to cradle*" theory is

substantially inspired by nature, pushing for the developing of human industrial activities towards the adoption of existing natural models (so called "*bio-mimetic approach*").
In addition to the illustrated connections between circular economy fundamentals and the proposed applications for macro-algae, there are some more interesting and explicit links related to specific legal purposes within the European legislation pack on waste. Algae should be quite interesting also dealing with two specific purpose of the European Commission on:

- ✓ "*marine litter*" - Member States have to recognize the main sources of marine litter, they have to adopt preventive measures to reduce it. Commercial restrictions are included for the more problematic products;

- ✓ *"food waste"* – in the world millions people still suffer for hunger, food waste cannot be accepted, and it represents a priority in the implementation of a circular economy (*Frans Timmermans, Vice-President of the European Commission);*

- ✓ "*organic waste*"– the European legislation pack on circular economy imposes to each Member States the adoption of measures to support recycling for organic waste *(Directive 2008/98/EC, article 22).*

Together with the related R&D activities, the auspicated and simultaneous growth of circular economy and bioeconomy gets a clear relevance to achieve the SDGs.
Great help for this purpose and for the development of related research and projects could result from the introduction of the *Shared Pilot Framework (SPF)* in Italy. These units are open pilot public plants that are standing for permitting technological innovations within industrial activities. *SPF* are still not introduced in Italy~~,~~ while showing off their excellent potentialities in Netherlands ("*bioprocess facility*" in Delft) and in Belgium ("*biobased Europe pilot plant*" in Ghent).
According to Intesa San Paolo - Direction studies office, the Italian national economic value of bioeconomy is high; 251 billion euro was the value in 2015. Thus, considering the opportunity to commit to shared long-term investments (such as *SPF)* could represent an affordable chance to adequately support valiant and challenging projects and encourage the transfer results from research to industrial activities.

4. *ALGAE, EXPERIENCED APPLICATIONS*

This chapter reports the short description of some existing applications for algae, experienced all over the world and just developed to meet sustainable circular economic challenges of our times.

Within the thorough list in the following *Table (Table n. 5)*, the main existing applications for algae are briefly reported, each one supported by self-research activities results and documented by selected scientific publications. For the sake of simplicity, in the reported framework, known innovative applications for algae are divided in three groups by their final purpose:

INTERESTING EXPERIENCED APPLICATIONS FOR ALGAE

ALGAE as BIOMASS	***Brief description***	***Top issues related to circularity***	***References***
algae for feed and extraction of proteins	The utilization of microalgae is converting it into food, chemical feed, and pharmaceuticals due to their abundant protein content presents ~~as~~ an attractive option to be explored. Protein is one of the essential products in a microalgal bio-refinery, as microalgae are naturally rich in proteins. Due to the nutritional and environmental advantages of algal protein, it is critical to producing algal protein in a sustainable equilibrium. Some studies reported that *Chlorella* is a protein-rich microalga and serves as a potential feedstock for animal feed (Bleakley and Hayes, 2017).	The consumption of food, water, and natural resources have significantly increased in the past decades. Agricultural and livestock activities directly influence the waste generation and land use significantly (Gasparri et al., 2013). Several conventional products need alternative sustainable and emerging materials as feedstock. Algae provide a potential method for producing high-value products in the circular economy concept with enhanced protein titer, content, and productivity.	Lai, Y. C., et al. (2019)
algae as fertilizers, bio-stimulants and regulators of plant growth	Algae have been known for their beneficial effect on plants for centuries, but their market potential seems to be underestimated. As biomass, excluded from primary raw materials, and a rich natural source of compounds with high biological activity against stress factors, algae fit very well into recent European strategies for the chemical industry, including the production of fertilizers and pesticides. Accordingly, meeting the forthcoming regulation on plant treatment, algae-based bio-stimulants and plant protection products are a great solution for the future for assuring sustainable agriculture.	Reducing the use of mineral fertilizers and chemical products. Increasing biomass production by activating the natural ability of plants to respond to stress agents (abiotic and biotic stress). Limiting dependency on critical (primary) raw materials and increasing the use of second-generation sources.	Dmytryk, A., et al. (2019)

algae for bioplastics	The rapid accumulation of plastic waste is boosting international demand for renewable plastics with superior qualities. Higher plants, microalgae, and cyanobacteria can drive solar-driven processes for the production of feedstocks that can be used to produce a wide variety of biodegradable plastics, as well as bioplastic-based infrastructure that can act as a long-term carbon sink.	An example of the global scale of plastic pollution is the *Great Pacific Garbage Patch,* which covers an area of around 1.6 million km^2 and is expanding rapidly. It has the consistency of plastic soup. Most particles within this soup have a diameter of a few millimetres. Microplastics account for about 13.2% of plastic waste by mass and concerns regarding health-related problems are increasing due to their entry into the food chain. Algae could play a key role in boosting the production of renewable plastics with superior qualities. Algae have a strategic convenience preventing any competition with feed production and by ensuring no further land consumption.	Karan, H., et al., (2019)
algae as source of phycocyanin and other industrial pigments	Algae are morphologically diverse and widely distributed photosynthetic organisms recognized as an excellent source of pigments, including chlorophylls, carotenoids, and phycobiliproteins. Algal pigments are in prime focus as they can be produced in large quantities in a renewable manner. All these pigments are of great potential in biotechnological applications, including nutraceuticals, pharmaceuticals, and cosmetic industries as well as in biomedical research and clinical diagnostics.	Every application for pigments extracted by algae totally match the fundamentals of a circular economy, by reducing waste, minimizing the use of minerals, chemicals, and raw materials and allowing the entry of eco-designed products in the market, with huge benefits for health and the environment	Dasgupta, C. N. (2015)
ALGAE as BIOENERGY	***Brief description***	***Top issues related to circularity***	***References***
Biorefinery and biofuels production	The development of CO_2-neutral fuels is one of the most urgent challenges our society faces to reduce gaseous emissions and their consequential climatic changes, greenhouse, and global warming effects. Microalgae have been called 'green coal' due to their capacity to produce and store energy-rich oils and carbohydrates, and currently have been receiving considerable interest as a potential feedstock to produce sustainable transportation biofuels. Microalgal biomass can be converted to biofuels through biochemical and thermochemical	Innovative biorefinery could be an interesting example of how to reduce microalgal biomass production costs, providing treatment to brewery effluents, with the generation of valuable biomass for several different applications (biofuels, bioactive compounds, and biofertilizers/soil conditioners), which could offer economic and environmental benefits to the brewery industry, and contributing to a real circular economy.	Ferreira, A., et al., (2019)

	conversion. Biochemical conversion technologies mostly involve microorganisms and enzymatic and chemical processes such as fermentation (bioethanol and hydrogen), anaerobic digestion (biogas), photobiological hydrogen production and transesterification techniques (biodiesel). Thermochemical conversion involves the thermal decomposition of organic compounds present in the biomass using liquefaction, gasification or pyrolysis (bio-oil, biochar, biogas, and syngas).		
ALGAE to BIORECOVERY	***Brief description***	***Top issues related to circularity***	***References***
wastewater treatment	The adoption of microalgae-sourced products depends on economic feasibility. In the case of fatty acids, it is crucial to obtain high lipid yield, especially in the form of storage lipids (TAGs). However, the production of these lipids often comes into competition with the microalgae biomass, resulting in a decrease in growth. A microalgae culture integration project was conducted in an industrial park in Canada to cultivate microalgae from the park's wastewaters and then obtain products from the biomass. Different deficiencies and stresses were tested to evaluate what condition allowed the induction of the highest lipids accumulation without compromising the growth of microalgae.	Algae's plantations can improve life below water and reduce water pollution. Algae can have extraordinary potential both by monitoring water pollutants and by treating ecologically wastewater.	Belanger-Lepine, F., (2018) .

Table n. 5– main experienced innovative applications for algae. Source: Author's elaboration on referenced publications

5. *FOCUS ON TWO INNOVATIVE EXPLOITATION OF INFESTING SEAWEEDS FULLY INSPIRED BY CIRCULAR ECONOMY*

A more in-depth analysis of the peculiarities of some research activities on overrun and infesting macro-algae is provided in the present chapter. These activities, as reported in the introduction, get, in the current time, a main interest matching the principles and the key characteristics of a circular economy *(fig. 2 and tab. 4).*

5.1 Wastes becoming resources: overrun macroalgae aimed to the extraction of bioactive components and disposed as active bio-sorbent of pollutants.

Marine algae and their extracts have gained much importance developing of nutraceutical products due to their high content in bioactive compounds that have attracted great interest in the pharmaceutical industry as a source of raw materials. Their high level of biodiversity makes them a considerable reservoir for active compounds as they can produce a great variety of secondary metabolites characterized by a wide range of biological activities. Many previous studies demonstrated the remarkable benefits of seaweeds on human health and protection against chronic disease due to their content in proteins, lipids and fatty acids, polysaccharides, and antioxidant compounds. It has been demonstrated that fatty acids extracted from marine algae block the growth and spread of human breast cancer. Besides, polysaccharides and terpenoids from brown algae have demonstrated to be promising bioactive molecules with anticancer activity. For example, *Padina pavonica*, a marine brown seaweed, member of the Dictyotaceae familia widespread throughout the world in warm temperate to tropical locations, is used above all as a sensor or marker to study pollution levels in the sea and, in general, in the marine environment, but it also proved to be rich of sterols, lipids, polysaccharides, carotenoids, polyphenols and fibers that can be exploited for the production of cosmetics, nutraceuticals, drugs. Extracts of *Padina pavonica* proved to be effective in "in vitro" and "ex vivo" experiments as pro-apoptotic agents towards primary human cancers (*Bernardini, 2018)* but also as potent pro-functional compounds potentially useful for the treatment of human osteoporosis (*Minetti, 2019*).

Macrophytes and macroalgae represent an environmental problem in coastal areas due to the increasing eutrophication of coastal waters (*Morand and Briand, 1996*). Macroalgae are naturally growing in coastal eutrophic ecosystems producing great quantities of biomasses (*Lenzi et al., 2003; Bastianoni et al., 2008; Giovani et al., 2010*). In such ecosystems, naturally produced macroalgae biomasses are mechanically harvested and managed as waste. These management actions need important human actions supported by notable economic resources representing a critical aspect for municipalities (*Bastianoni et al., 2008*). Only to give some reference numbers, in the

Orbetello lagoon (Italy), from 2002 to 2006, on average 27,098.02 tons (6,774 tons per year) of macroalgae are harvested (*Ludovico, 2006*) with an associated expense of about 600,000 Euros per year (*Bastianoni et al., 2008*).

On the contrary, macroalgae represent a resource. In fact, multiple possible uses were theorized and tested on macroalgae from the Orbetello lagoon during the last decade. Among them, the use of microalgae for the biodiesel production is well studied as it represents an interesting alternative to fossil fuels and a useful alternative energetic supply for developed countries reducing greenhouse gas emissions and achieving efficiency and sustainability (*Bastianoni and Marchettini, 1996; Belarbi et al., 2000; Mata et al., 2010; Cooney et al., 2011*). Some recent research focused the chance to use macrophyte biomasses for bio-oil production with interesting results in term of extraction efficiency even if results are far to be encouraging to develop a sustainable industrial plant from an economic point of view starting from biomasses harvested in the Orbetello lagoon (*Bastianoni et al., 2008; Renzi et al., 2013*). Recent research focused on the chance to extract oils from microalgae to produce biofuels suggested interesting results (*Spolaore et al., 2006; Mata et al., 2010*). Nevertheless, the same approach turns on macroalgae from the Orbetello lagoon resulted not so efficient in terms of oil recovery (*Renzi et al., 2013*).

Recent studies evidenced that macroalgae could be suitable as bio-sorbent for removing cations and treating a high volume of low-concentration complex wastewaters (*Wang and Cheng, 2009*).

Recent research was developed to evaluate if macroalgae biomasses could be used as raw materials to build biofilters to purify cations polluted wastewaters using Fe^{2+} as a representative element. Data were collected on dried tissues. Furthermore, experiments were performed, also, on tissues organic-extracted to remove biomolecules of pharmaceutical interest and dried. This test aimed to evaluate if residuals after the preliminary extraction of pharmacological-active biomolecules could produce biofilter.

Different factors of interest were tested separately to evaluate the efficiency of removal according to: i) species (three levels, fixed, *C. linum, R. cirrhosa, V. aegagrophyla*); ii) biomass/water ratios (three levels, fixed, 100 g/L, 50 g/L, 10 g/L); iii) pollution levels (three levels, fixed, 0.1 g/mL, 0.05 g/mL, 0.01 g/mL); tissue pre-treatments (two levels, fixed: dried, organic-extracted and dried). Results were statistically analyzed to evaluate the significance of observations by univariate approaches (t-test, F-test, $p<0.05$ was considered slight significant *, while $p<0.01$ was considered significant **). Macroalgae biomasses were collected by the local harvesting plant in Orbetello (*Ludovico, 2006*); species selected were the following *Chaetomorpha linum* (O.F. Müller) Kützing, 1845, *Valonia aegagrophyla* Kützing, 1845, *Ruppia* spp. (*Giovani et al., 2010*). Tissues were completely dried by the oven (60 °C till constant weight) to improve absorption performances in both cases (raw material and biomass previously extracted). Experiments were performed in triplicate to evaluate the standard deviation among replicates. The efficiency of absorption on biomass was evaluated by measuring residual Fe2+ amount added in water before the exposure to biomass. Concerning the removal efficiency of ionic metals, the comparison among results on absorption efficiencies is reported in *Table n. 6*. The better efficiency is associated to *V. aegagrophyla* (95.5%; 2.8 SD) at high biomass/water ratio (97.8%; 0.9 SD), and in high polluted water at Fe2+ level of 0.1 g/mL (95.9%; 1.9 SD). Observed trends are tested by a univariate statistic approach to evaluate the significance of observed performances. Results evidence that tested species do not significantly affect absorption efficiency concerning both average and variance. On the contrary, results evidence that biomass/water ratios could affect absorption efficiency in terms of average recoveries (50-10 g/L and 100-10 g/L) and variance (100-50 and 100-10 g/L). This study evidence that 10 g/L is lower efficient in metals absorption than higher tested biomass/water ratios, also producing the highest variability of performances. Furthermore, results evidence that tested highest biomass/water ratios are efficient in removing cations at levels ranging within 0.01-0.10 g/mL. No differences concerning removal performances were recorded compared results obtained on raw dried tissues and on dried biomass previously extracted (t-test; F-test, $p>0.05$).

Research on the development of new energy supplies and green energy production are notably increased in the last decade due to the worldwide need to by-pass fossil fuels and to reduce greenhouse gas emissions (*Mata et al., 2010*). Recent research focused on the chance to extract oils from microalgae to produce biofuels suggested interesting results (*Spolaore et al., 2006; Mata et al., 2010*). Nevertheless, the same approach turns on macroalgae resulted not so efficient in terms of oil recovery (*Renzi et al., 2013*). Macroalgae are naturally growing in coastal eutrophic ecosystems producing great quantities of biomasses with any human effort that are managed by local municipalities with important costs (*Lenzi et al., 2003; Bastianoni et al., 2008; Giovani et al., 2010*). Recent studies evidenced that macroalgae could be suitable as bio-sorbent for the removal of cations and to treat a high volume of low-concentration complex wastewaters (*Wang and Cheng, 2009*). Results obtained in this study supported previous research highlighted high absorption efficiency (over 80%) also at the lowest pollution level tested (0.01 g/mL = 10,000 mg/L). These values are about 200 times the concentrations of cations measured in spring water from polluted mining areas (*Basset et al., 2017*). In this context, macrophytes biomass filtering of water could be able to reduce the pollution of superficial water, improving ecosystem health and reducing significantly mining impacts. Data collected in this study are encouraging and show that macroalgal wastes could be changed into a resource for coastal ecosystem performing harvesting of biomasses. On the basis of these preliminary results, further research should be developed to evaluate efficiency of removal from in vitro mixture of cations and from polluted water samples. In this study, tests were performed on static systems and are representative of the removal efficiency from static wastewater. Further tests to evaluate the removal efficiency of biomasses on running water should be performed. Furthermore, the efficiency of removal from polluted waters should be tested through in field experiments, and a prototype of a large-scale filter simulator should be developed and tested to model and evaluate the commercial feasibility of the removal process.

Species		t-test		F-test	
C. linum	*R. cirrhosa*	0.745	NS	0.748	NS
R. cirrhosa	*V. aegagrophyla*	0.585	NS	0.328	NS
V. aegagrophyla	*C. linum*	0.832	NS	0.502	NS
Biomass/water ratios		t-test		F-test	
100 g/L	50 g/L	0.104	NS	0.029	*
50 g/L	10 g/L	0.035	*	0.189	NS
10 g/L	100 g/L	0.015	*	0.002	**
Pollution level		t-test		F-test	
0.10 g/mL	0.05 g/mL	0.336	NS	0.006	**
0.05 g/mL	0.01 g/mL	0.341	NS	0.009	**
0.01 g/mL	0.1 g/mL	0.969	NS	0.843	NS

*Table n. 6. Comparison among statistics performed on absorption efficiencies. Taxonomic identification of species used in this study was performed by Dr. A. Giovani (University of Siena). Table reports p values and associated significance for tested couples. NS = not significance, * = slight significance, ** = strong significance. No significant results comparing dried and preliminary organic-extracted dried macroalgae.*

5.2. The use of the electrospinning technology on overrun seaweeds to create biocompatible polymers

Among the technological processes that could allow an easy fabrication of plastics from natural resources (e.g., polymers from microorganisms, plants, algae, waste products) giving life to newly born simple or composite materials for specific uses, electrospinning technology looks particularly interesting because it shows great flexibility in terms of materials choice (*Bin Ding, 2019).*

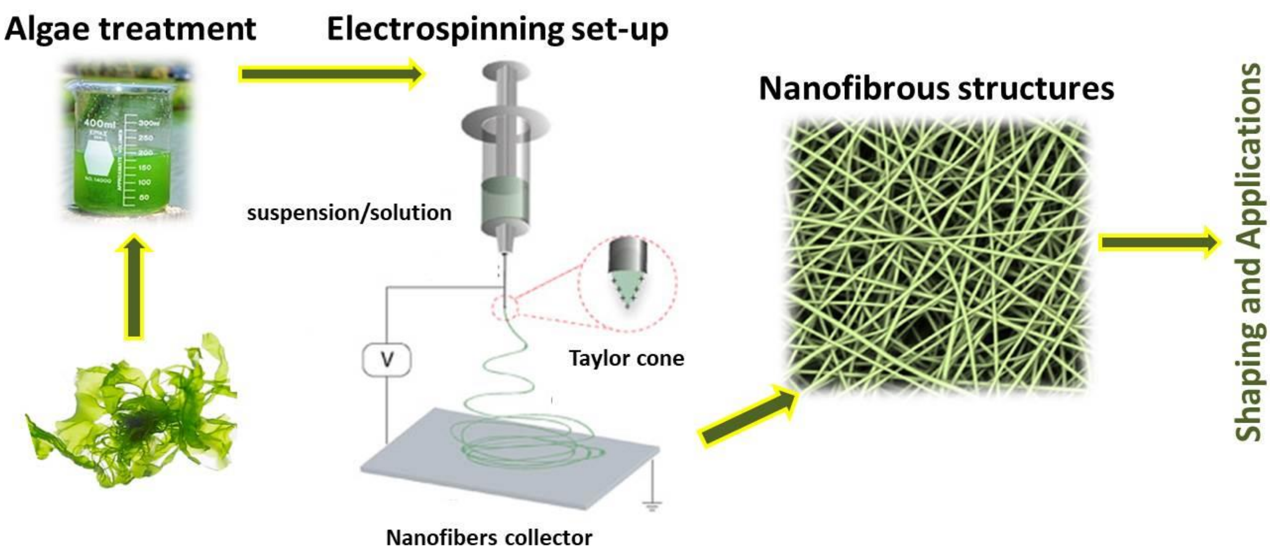

Fig. n. 4 – Process representation to realize nanostructured biomaterials, using the electrospinning technologies on overrun seaweeds. Source: author's elaboration.

The term "electrospinning" derives from "electrostatic spinning", and even if its process is known from the early 1900s, it has been arousing considerable interest for the last 20 years due to its versatility and ability to consistently produce micro- and nano-fibers with high surface-to-volume ratio, simply starting from polymer solutions. Electrospinning apparatus is simple, easy to use and low operating cost. The process can be scalable to industrial dimensions, offer specific fibers configurations and guarantee reproducible products *(E. Kny, 2018).* The process is commonly conducted at room temperature with atmosphere conditions. Because of these features, such a technology works in agreement with the worldwide demand for producing renewable bio-based raw materials to replace the petroleum-based raw materials and polymers. Therefore, algae biomass can be an excellent source for designing ES eco-friendly, biodegradable, bio-renewable, green, and low impact tools, like filters, packages, sensors, catalysts, smart textiles, bioscaffolds, delivery fabrics, etc. To clarify the reasons of above, brief notes on the principle of operation are reported here below. ES works using a polymeric solution loaded into a syringe and connected to a metal needle (spinneret). A high voltage (commonly ranging between 5-40 kV) is then applied to the solution, and a grounded or oppositely charged target (collector) is placed some distance from the polymer solution to capture and collect the produced fibers (aligned, woven-non-woven, twisted, etc.). When the electric field is applied to the surface of the solution drop, it elongates to form a conical shape and then a charged jet travelling through the path up to the collector. The instability region, where bending and whipping movements, together with solvent evaporation, cause the jet thinning and splitting, fabricating spraying droplets or separated fibers deposited on the collector. The success of the electrospun deposition depends mainly on solution parameters as the polymer molecular weight, the concentration, the viscosity, the conductivity and the surface tension. Furthermore the environmental conditions (e.g., temperature and humidity) and the process parameters (e.g., potential applied, feed rate, distances between spinneret and collector, etc.) are also noteworthy. By properly tuning these parameters, it is possible to obtain nanofibers with the desired morphology and diameter. Furthermore, different structures of nanofibers, such as core-shell, blends or composite, hollow, and porous can be obtained by using special spinnerets or by playing with solvent type and ambient conditions. The resulting nanostructured materials often feature high porosity, stability, permeability, and a large surface-to-volume ratio.

As previously described, marine algae can be supposed to be a significant biomass source to be used as cradles for the extraction of biomaterials and the production of ES nanostructured materials with unique properties and remarkable applications.

Algae-based materials can be provided in the form of algal polymers, polymer blends, and composites resulting from algal biomass or biomolecules mixed or encapsulated within polymeric matrices *(Teboho Clement Mokhena, 2020)*.

As reported before, important algal polymers include polysaccharides and sulfated polysaccharides such as carrageenan, agars, alginates, and polyhydroxyalkanoates. Additionally, algal biomass and biomolecules can be successfully used as precursors of several biopolymers such as polyethylene, polyurethane, and polyesters *(Khalid, 2017).*

Finally, the incorporation of algal polymers and biomass into synthetic polymers (when bio-polymer cannot be used) results in mechanical properties and biodegradability implementation *(Yolanda Freile, 2017).*

Coaxial ES or core-shell ES was developed about ten years ago and it became extensively studied in many different fields such as drug delivery and nanofluidics *(A.L. Yarin, 2017).* In fact, with this technology, it is possible to impart specific functional properties onto the surface of the nanofibers (shell solution), while keeping the intrinsic properties of it (core solution). Furthermore, it allows encapsulation in the core or wrapping as a shell of non-spinnable polymers or non-polymeric materials. Electrospun fibers have been considered interesting carriers for active compounds since their diameters range from the micro to the nanoscale and possess large surface area and small inter-fibrous pore size with high porosity that are easy of functionalization. In fact, the electrospinning process is currently one of the most promising encapsulation techniques. Encapsulation is required for the protection of active compounds that also helps in improving its stability, bioavailability, and controlled release.

Algal polymers and their blends have been electrospun for packaging, agriculture, dairy, and food pertinence, drug delivery, low-fat sausages, and cell encapsulation/grafting based on their exceptional properties such as thickeners, stabilizers, emulsifiers, gelling, and film-making properties. Examples of bio-based plastics include polymers as polyhydroxyalkanoates (PHAs) and polyesters (PE), which are used for a number of purposes, including food packaging and agriculture *(Kabasci, 2014).* For instance, poly-3-hydroxybutyrate (PHB) is a thermoplastic polyester that occurs naturally in bacteria (*Ralstonia eutropha, Bacillus megaterium, etc.)*. Even though PHB is biodegradable and with some excellent features for a lot of commercially available plastic tools, this bioplastic has been updated bit expensive and time-consuming to produce *(N. Sharma, 2019).*

Recently, brown seaweed *Sargassum* sp. was used as a feedstock to produce polyhydroxy butyarte (PHB) using *Cupriavidus necator*, a soil bacteria. In order to release monomeric sugars, dilute acid hydrolysis of *Sargassum* sp. biomass was followed by enzymatic saccharification, in presence of ammonium sulfate and NaCl, with high PHB yield (0.74g/g reducing sugar) (*Azizi N., 2017).*

For example, electrospun PHB nanostructured membranes based have been designed, developed, and investigated as potential tools for agriculture (*De Cesare, 2019)* designed proper membrane of polyhydroxy butyrate (PHB) blended with polycaprolactone and loaded with catechol (easy to be handled) to make available insoluble iron from the surrounding soil/liquid to the plants' roots. PHB was also used in combination with polyaniline (PANi) (*Macagnano, 2016)* to design electrospun conductive sensors for gas sensors, whose sensing features could be driven by the environmental moisture. The nanofibrous layers obtained through electrospinning technology carried out directly on chemoresistors resulted in highly porous membranes with fast responses and high sensitivity to NH_3. Thus, PHB in combination with recyclable polystyrene (PS) and a known concentration of mesoporous graphene was electrospun in a single step to create novel selective gas sensors. The blending of the two thermoplastics allowed the development of rough and porous nanofibers stable and capable of working between 40 and 80°C and detect volatile organic compounds and gases in a selective way. More in detail, the sensor resulted highly sensitive and selective to acetic acid at 40°C, but the sensitivity fell down, decreasing by 96% when the sensor operated at 80 °C. However, at higher temperatures, the sensor increased hugely its sensitivity to NO_2. The selectivity of such sensors could be easily and quickly modulated by the working temperature *(J. Avossa, 2018).* Alternatively, algal extracts can be co-electrospun with synthetic polymers to improve some polymer features. Poly (vinyl alcohol) (PVA) is a water-soluble and biodegradable semicrystalline polymer, widely used in the food packaging in combination with additional compounds to it specific functions *(Zainab Waheed A., 2019).* Electrospun PVA fibers loaded with hydrophobic biopolymeric matrices such as PLA (polylactic acid) have been recently investigated for food packaging. PLA is currently used as the most sustainable alternative to petroplastic since it is compostable and biodegradable. Presently, PLA production is related, such as in many other bio-polymers, to the use, therefore the consumption, of important resources used to feed humans or animals (e.g. sugar cane and beets, corn, wheat, etc.). More recently, seaweeds have been processed to produce lactic acid that is the PLA precursor *(Hwang, 2012)* On the other hand, the main PLA drawbacks are its low thermal stability, as well as the low barrier and mechanical performance. The combination of each compound is designed to improve, in synergy, the package performances. Thus, electrospun PVA fibers enhanced the PLA crystallinity, the oxygen barrier and mechanical performance of the resulting plastic membranes. *Arrieta, et al.* (2018), obtained, in a single step, PVA/PLA electrospun fibers loaded with triethyl citrate (an algae extract) having the double function of antioxidant active food packaging and highly flexible film *(P. Arrieta, 2018).*

Microcrystalline cellulose (MCC), a type of cellulose that has undergone purification and partial hydrolyzation, is also commonly used in several industrial activities like food production, pharmaceutical, cosmetics, animal feeds and, recently, bio-sensors. Generally, this compound is produced from wood or plant biomass through a number of physical and chemical treatments. Microcrystalline cellulose from algae can be used to develop composite and reinforced polymer materials (e.g. PLA+MCC), with properly selected physical and mechanical properties. Therefore, it can also contribute to filtration systems and ecological building (*A. Gaitan, 2018*).

Electrospun nanofibers, from natural polymers have also been used in regenerative medicine, including tissue engineering applications, due to the similarities of ES nanofibers to the natural extracellular matrix components which facilitate attachment and proliferation of cells. Seaweeds contain various growth factors that can promote the regeneration of various tissues. For instance, phlorotannin, the main component of the brown alga *Ecklonia cava*, can improve bone regeneration by stimulating alkaline phosphatase (ALP) activity and inducing calcium deposition.

A description of the potentials of an electrospun 3D-scaffold made of polycaprolactone (PCL)/phlorotannin micro/nanofibres containing different algal tannins, as powerful bioactive material for enhancing bone tissue growth is described by Kim et al. (2012). The number of recent studies concerning electrospun algal polysaccharides and their derivatives is increasing dramatically. Alginate is an anionic polysaccharide present in the cell walls of brown seaweeds. It contains blockwise structures of (1,4)-linked β-D-mannuronic acid (M) and α-L-guluronic acid (G) residues. Still, the actual chemical structure of the alginate varies from one genus to another. The composition, sequence, and molecular weight generally determine the physical properties of alginate. Latter can form hydrogels, porous sponges, beads, and microfibers for a plethora of applications. Its biocompatibility, low toxicity, non-immunogenicity, relatively low cost, and simple gelation behavior with divalent cations such as Ca2+, Mg2+, Ba2+, and Sr2+ makes it an excellent candidate for biomedical applications. However, the production of submicron alginate fibres by electrospinning is still challenging due to its high viscosity, even at low concentrations (2% w/v in aqueous solution). Conversely, a concentration <2% w/v cannot guarantee suitable polymer chain entanglements needed to obtain a continuous jet that, in turn, is necessary for the production of homogenous fibers. The combination of alginate with additional polymers or strong polar solvents seems to be a successful strategy to get functional fibers. *Nie et al.*, reported that alginate could be successfully electrospun by using glycerol as a co-solvent. Smooth and uniform alginate nanofibers were provided by simply modifying the volume ratio between water and glycerol. The role of glycerol in the ES process concerned mainly the breaking up of the strong inter- and intramolecular hydrogen bonds among the polymer chains *(Huarong Nie, 2008).* Sodium alginate (NaAlg) was electrospun from aqueous solution blended to polyethylene oxide (PEO), a biofriendly synthetic polymer, exhibiting good uniformity, structural integrity and increased tensile strength *(C. Hu, 2015).* Its cellular compatibility with cartilage chondrocyte-like cells was proved by *Vigani et al*., (2018). The cells showed a good adhesion on the alginate/PEO nanofibrous matrices maintaining their characteristic phenotypes and cell viability of approximately 95% *(Vigani B., 2018).*

6. CONCLUSIONS

Algae are rich of novel and biologically active metabolites. The proper development and study of marine algae compounds will help in, agri-food, medical product, and cosmeceutical development. In some circumstances and conditions, too dense and numerous seaweeds can compromise marine ecosystems' health and implicate huge damns for fishing activities and local communities. For these reasons, infesting and overrun algae are often considered waste for disposal, with enormous costs for local administrations and consequent environmental impacts. Therefore, the exploitation of overrun seaweeds, through the development of innovative research activities, could allow the simultaneous achievement of several goals on the road to a circular economy and sustainable management for waste and resources.

For their great industrial exploitation potential and availability, seaweeds can certainly compete with synthetic chemical products for health and cosmetic applications. The use of macroalgae and their extraction derivatives to counteract skin aging, depigmentation, and thickening applications in the cosmetic industry, is today object of advanced research in academic and industrial fields. A wide range of metabolites, such as antioxidants, anti-inflammatory agents, alginates, polysaccharides, vitamins, and peptides, must be evaluated and investigated for green eco-sustainable cosmeceutical preparations, following the principles of the circular economy.

Like electrospinning, proper technologies can fit a circular economy strategy where seaweeds derivatives can be easily redesigned, modulated, and properly functionalized to be converted in a plethora of more sustainable outfits, like sensors, bio-scaffoldings, smart tools for agriculture, packaging, etc.

Considering the forthcoming rules on waste management and circular economy, there is a significant opportunity to launch overrun seaweeds based products, due to their real healthy properties. This is also in accordance with the newest European strategy, which points to the potential development of algae in the direction extracting high-value compounds, rather than using raw biomass for incineration. The creation of new bio-based high value chains promoted by the new regulation would enhance the diversity of and access to such products and positively influence the European industries' sustainability.

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