Biochar in modern agronomic practices.

Enabling soil bioremediation,
with boosting environmental
and economic benefits.

Residue

PRIMA
PARTNERSHIP FOR RESEARCH AND INNOVATION
IN THE MEDITERRANEAN AREA

This project is part of the PRIMA
programme supported by the
European Union

Summary

1.

Introduction

Residue project

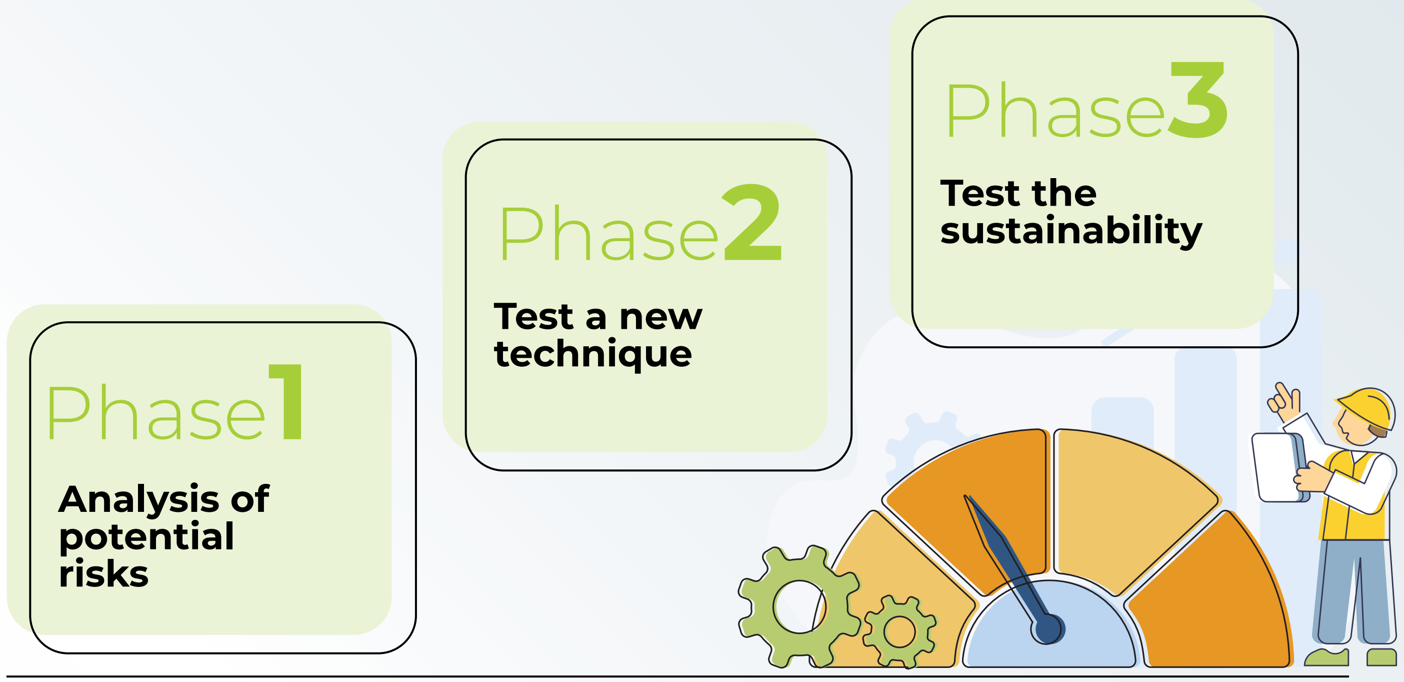
RESIDUE is a 36-month project funded under the call **"Management of Water"** of the PRIMA Programme. The project relies on the improvement of the safety of agricultural products grown in countries which are obliged to use waste materials for irrigation and fertilisation of crops development of an innovative technology that significantly reduces the risks of transferring organic contaminants to agricultural products.

PRIMA Programme – Partnership for Research and Innovation in the **M**editerranean **A**rea – is an ambitious joint programme in the frame of Euro-Mediterranean cooperation.
It consists of European Union Member States, Horizon 2020 Associated Countries and Mediterranean Partner Countries on an equal footing basis with the Participation of the European Commission. Currently, 19 countries are committed to the initiative (Algeria, Croatia, Cyprus, Egypt, France, Germany, Greece, Israel, Italy, Jordan, Lebanon, Luxembourg, Malta, Morocco, Portugal, Slovenia, Spain, Tunisia and Turkey).
The mission of the PRIMA initiative relies on achieving, supporting and promoting integration, alignment and joint implementation of national R&I programmes under a common research and innovation strategy to address the diverse challenges in water scarcity, agriculture and food security.

For this purpose, the thematic areas of the PRIMA Programme are:

- Integrated and **sustainable management of water** for arid and semi-arid Mediterranean areas.
- **Sustainable farming systems** under Mediterranean environmental constraints.
- **Sustainable Mediterranean agro-food value chain** for regional and local development.

A special focus is placed on utilising locally available resources and making the new techniques easily applicable in common agricultural practice. Scientifically based characterization and optimization of treatment procedures enables the application of these methods to similar waste materials available in other water-scarce locations. In this project, safe ways are proposed to improve soil functions by leading to in situ removal and detoxification of organic pollutants introduced by waste materials, including wastewater used in agriculture.
The project follows a three-phase approach: in the first phase, potential risks determining the use of wastewater (WW) in agriculture will be analysed and experimental research will be conducted to fill current gaps. In the second phase, a new composting technique developed for sewage sludge will be tested, based on the application of biochar. The biochar will be produced from locally available waste materials. The effectiveness of the new process in reducing contaminants will be tested by following the fate of selected organic substances that are typical contaminants in sewage sludge. The last step is to experimentally test the sustainability of in situ substrate detoxification of irrigated wastewater in modified soils. Laboratory and greenhouse experiments will be carried out with 14C radio-labelled organics to understand their fate and detoxification processes. Different scales of approach will be used, from laboratory experiments to outdoor field experiments conducted under realistic agricultural conditions.



The countries involved are Israel, Spain, Germany and Italy, in each of which water is one of the most important factors for agriculture. This is particularly applicable to Israel, where, to exploit all available water sources, WW is widely used for irrigating fields. More than 50% of this country's irrigation is done with treated wastewater. For Spain, the high rate of sewage sludge and wastewater used in agriculture makes this project extremely important. The project will provide new insights into the risk associated with this practice, in relation to chemical pollution and food safety issues, and a strategy on how to reduce this risk. For Germany, the results will also be of great value for the safety and quality assurance of sewage sludge application in agriculture. There is no current need in this country to use WW for irrigation, but the application of sewage sludge is still an important way of ensuring a valuable supply of nutrients to agriculture. Sewage sludge composts may find wider application if the risk of contamination by organic contaminants can be significantly reduced. In Italy, the project will support the policy on recycling routes for sewage sludge use in agriculture as low-cost organic fertilizer. Food safety implies the prevention of pollution by wastewater as source by appropriate pre-treatment before use in agriculture. However, the regulation of purified wastewater and sewage sludge in agriculture in Italy is very fragmented, especially between the southern and northern regions.

Biochar in modern agricultural practices

Biochar is a carbon-rich product obtained through different heating processes of material of vegetable origin, generally biomass, at very high temperatures and low oxygen concentrations. The definition is due to the proposal of the International Biochar Initiative IBI as a result of the union of the words bio (from the Greek, life) and char (from the English, coal), which indicates their prevalent use in agriculture and phytosanitary defence[1]. The composition of the starting raw material, such as lignocellulosic waste of forest origin (wood chips, pellets, bark) and agro-industrial waste (straw, shells, rice husks), have a crucial role in determining the characteristics of the biochar, influenced by the different presence of cellulose, hemicellulose, lignin and minerals and their behaviour during the thermal production process. Thanks to its crystalline structure and chemical-physical properties, biochar can be used as an amendment in agricultural practices, bringing numerous benefits. In particular, the biochar applied in drought contexts and leached soils contributes to the retention of nutrients, the conservation of humidity and water, preserving the correct pH of the soil and improving the agricultural yield thanks to the stimulation of the root system and the preservation of the microbiota.
Concerning the environmental sustainability profile, biochar allows the storage of carbon in the soil, helping to reduce the use of chemical fertilisers and the consequent emissions of nitrous oxide and ammonia, as well as to decontaminate soil and water from numerous heavy metals.
Furthermore, biochar brings undoubted economic advantages for the farm thanks to a production process based on the valorisation of waste biological resources, with savings in amendments and production costs. Biochar fits into the European regulatory framework for organic farming, qualifying as one of the most useful allies in transitioning from traditional to organic farming. In fact, it has been identified by the Intergovernmental Panel on Climate Change (IPCC) as one of the important solutions to mitigate climate change and has been recognized as a Negative Emission Technology (NET), considering its ability to actively remove CO2 from the atmosphere.
The Guide illustrates the advantages of its application at an environmental and agricultural level and its production from wastewater.

Biochar

improve the
chemical-physical
and microbiological
characteristics
of the soil.

2.

Biochar: origins and production methods

Biochar is a highly porous vegetable carbon produced through different heating processes of material of vegetable origin, at very high temperatures between 400 and 800°C and at low concentrations of oxygen[2]. From a chemical point of view, biochar differs from coal due to a composition characterised by high percentages of carbon (50-90%) and aromatic chemical structures, which give it important properties of promoting soil fertility[3].
Natural or synthetic substances, generally applied in agriculture as **soil amendments**, such as biochar, improve the chemical-physical and microbiological characteristics of the soil by creating a stable and porous structure that guarantees better conservation of organic matter, water availability and crop productivity.
The agronomic properties of biochar have been known for a long time. In the pre-Columbian era, the Indian civilisations used to bury charcoal to improve agricultural productivity in soils affected by substantial leaching. Evidence of this use is documented in the Amazon forest, where in the most fertile soils (Terra Preta dos Indios), there are high concentrations of vegetable charcoal[4].

Biochar production is optimized in the absence of oxygen: the more oxygen a production unit can exclude, the more biochar can be produced. For this type of process specific plants are needed, called biomass plants, which convert the energy content of the biomass into other forms of energy such as heat, in the case of combustion, or other energy carriers:

- Syngas in gasification plants.
- Biogas or biomethane from anaerobic digestion.
- Bioliquids or bio-oils from pyrolysis plants.
- Coal or other solid fuels from torrefaction or carbonization processes.

The **traditional method** of producing biochar for agronomic use is based on the combustion and carbonisation of lignocellulosic biomass in large piles, a practice still marginally employed in rural areas. There are mainly two methods to produce biochar: conservation burns or flame cap furnaces.

Conservation Burns

This is the simplest method to produce biochar, it only requires stacking the wood in a pile. Burns should ideally be conducted close to a pressurized water source because a significant amount of water to extinguish is necessary.

This method involves:

- Stacking the raw materials, which should be similar in diameter: the larger material should be placed in the center and the smaller diameters ones placed on the outside, towards the top.
- Once the stack is built, light a fire on top.
- The ideal time to extinguish the burn is after the fire has reached the bottom of the pile and a light coat of ash can be seen all over the material from top to bottom.
- The ideal way to extinguish storage burns is to spray the fire with pressurized water. It is important to ensure that the pile is fully saturated before setting off, as often the pile may appear to be extinguished but have a small number of live coals that can dry out the surrounding charcoal and start burning the pile again.

Flame Cap furnaces

This method uses a metal cylinder or box, with an open or closed bottom, so that the material can be charged throughout the combustion process, with the end of combustion occurring when the furnace is filled with biochar. This allows to increase the amount of biochar produced and to remove more slash material, making it ideal for forestry or agricultural production.

This method involves:

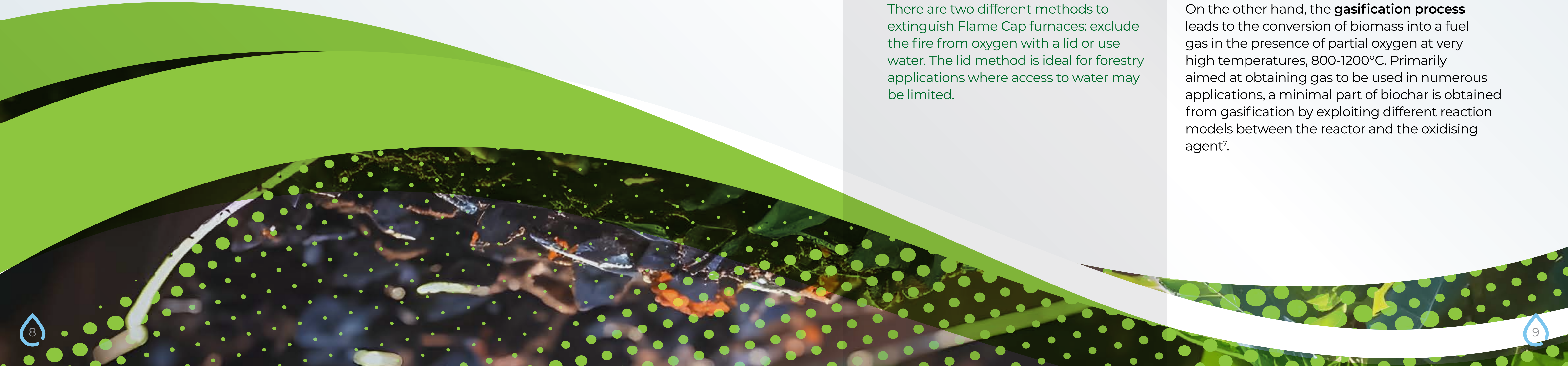
- Start a fire using fires and small sticks. If the kiln has an open bottom, allow air to enter from below to facilitate lighting the fire, simply shoveling several access points where the bottom of the cylinder meets the ground.
- When the fire is burning well (usually after 10-20 minutes), seal the bottom of the oven with dirt so that no air enters from the lower perimeter.
- Add material when you see that the top of the existing material develops grey ash on the outside. It is useful to add material of similar size to maximize combustion efficiency.
- Keep adding fuel until the kiln is full of charcoal or you run out of fuel. As the level of charred wood increases in the cylinder, the lower level of the outside of the cylinder should be cooler than the active combustion area, indicating that no oxygen is entering the furnace from below.
- There are two different methods to extinguish Flame Cap furnaces: exclude the fire from oxygen with a lid or use water. The lid method is ideal for forestry applications where access to water may be limited.

Burning wood in large fires generates ashes and fumes characterised by high concentrations of carbon dioxide (CO_2), carbon monoxide (CO), sulfur oxides (SOx) and nitrogen oxides (NOx) with harmful effects on humans and the environment[5]. Furthermore, in traditional production, the combustion at limited oxygen content, capable of forming biochar, affects only a minimal part of the total biomass, proving inefficient practice in exploiting natural resources[6].

To respond to the growing market need for more sustainable production and consumption approaches, biochar is produced on an industrial level through **pyrolysis, gasification and combined processes**.

Production by **pyrolysis** represents the preferred production process and uses different types of cellulosic starting biomass (wood, cereal straw) also waste (woody residues from pruning, oil plants and textile fibers), transformed by an endothermic process of heating at high temperatures (400-700°C) in the absence of oxidising agents (usually oxygen) into fuel gas (syngas), electricity, heat, and a solid by-product: biochar.
Different operating conditions lead to three respective classes of pyrolysis processes: slow pyrolysis or carbonisation (300-500°C), conventional pyrolysis (suitable to produce biochar), fast or flash pyrolysis (suitable to produce gaseous or liquid compounds suitable for fuel production).

On the other hand, the **gasification process** leads to the conversion of biomass into a fuel gas in the presence of partial oxygen at very high temperatures, 800-1200°C. Primarily aimed at obtaining gas to be used in numerous applications, a minimal part of biochar is obtained from gasification by exploiting different reaction models between the reactor and the oxidising agent[7].



Moreover, biochar can be obtained using two or more heat treatment technologies, called **combined processes**, capable of treating more complex and heterogeneous biological biomasses, such as urban waste. These approaches, however, tend to favour the production of high-value gases and lead to produce limited quantities of biochar.

The different final characteristics of the biochar and its uses will depend on numerous factors, such as the type of source material, but also the temperature, the pressure, the heating rate, its preparation steps (e.g. drying, chopping, sieving, pelletizing) and the duration of the production process itself[8].

The composition of the **starting raw material** (forestry, agro-industrial waste, organic waste) is different in the amount of hemicellulose, cellulose, and lignin, as well as the thermal behaviour during pyrolysis are crucial factors for the biochar yield. In this regard, high lignin contents ensure better process reactivity, stable carbon production and a consequent increase in effectiveness during agronomic applications. In commercial biochar production, wood and crop residues are the predominant raw materials due to their high availability and ease of handling. However, wood from different tree species (e.g., softwood vs. hardwood) and from different parts or growth stages of a tree (e.g., bark, sapwood, and heartwood) varies in density and chemical constitution. Since biomass materials differ in their lignocellulosic (i.e., lignin, cellulose, and hemicellulose) and mineral (e.g., N, P, K, S, Ca, Mg, Na and Si) compositions, the conversion of biomass materials from different sources into biochar at the same carbonization conditions results in products with different physical and chemical characteristics.
In general:

- Biochar derived from non-woody feedstocks such as grass, sludge and manure has compounds that make it more reactive;
- Biochar made from manure and sludge attenuates metals, contains a higher concentration of nutrients than wood-based biochar and is therefore more likely to be a good source of nutrients;
- High ash biochar, such as manure and coffee husk, may increase nutrient capture, although high initial nutrient concentrations may offset this and even contribute to nutrient loss.

The chemical composition of the biochar, made up of layers of carbon with a crystalline structure, is more structured with the increase of the **thermal conditions**, but above 800°C led to the loss of quality and yield of the process. Thanks to its structure and the associated chemical-physical properties, biochar is used in numerous applications ranging from the aforementioned agronomic practices to increase soil fertility, air and water bioremediation from harmful chemical substances up to the green building for the production of bricks, plasters and other cement-based mixtures with interesting properties of resistance to bending, insulation and absorption[1].

3.

Biological and chemical-physical properties of biochar

In modern agriculture, sustainable production approaches represent a new trend to preserve quality, food safety and protection of natural ecosystems. Over the last few decades, scientific research has intensified its efforts to identify agronomic methods based on organic amendments to reduce soil organic loss matter and limit climate-altering emissions. Chemical fertilisers are responsible for more than 19% of ammonia[9] and 25% of the CO_2 emitted into the atmosphere, soil acidification and biodiversity loss[10]. Today the dependence of industrialised countries on fossil fuels is leading to a progressive atmospheric re-carbonisation, with significant consequences on the health and well-being of the planet[11].
Thanks to the high porosity of its structure, biochar has demonstrated numerous beneficial effects as a promoter of the physical, chemical and biological properties of the soil and crop yields1, even in the most drought contexts and nutrient-depleted soils. Biochar persists in the soil for more than 2,500 years, does not decompose like other organic soil conditioners and resists chemical and microbial degradation. As a result, all the benefits last over time.

The biochar used in agronomic practices provides a significant contribution to improving the biological properties of the soil, including:

Nutrient retention and stimulation of the soil microbiota.
The composition of biochar is rich in carbon, hydrogen, nitrogen and other nutrients of mineral origin, such as potassium, calcium, sodium and magnesium, which are essential elements for plant live[12]. Biochar chemical structure is influenced by the starting raw material's nature and by the type of pyrolytic process adopted, which at lower temperatures (<500°C) also allows the accumulation and bioavailability of phosphorus, potassium and sulfur[1]. Thanks to these elements, biochar can compensate for the leaching in soil caused by the flow of rainwater,

thus increasing plant growth and limiting the use of fertilizers1. Biochar is also an ideal substrate for growing a large variety of microorganisms; soils with activated carbon increase 125% in microbial biomass compared to the unfertilised counterpart.

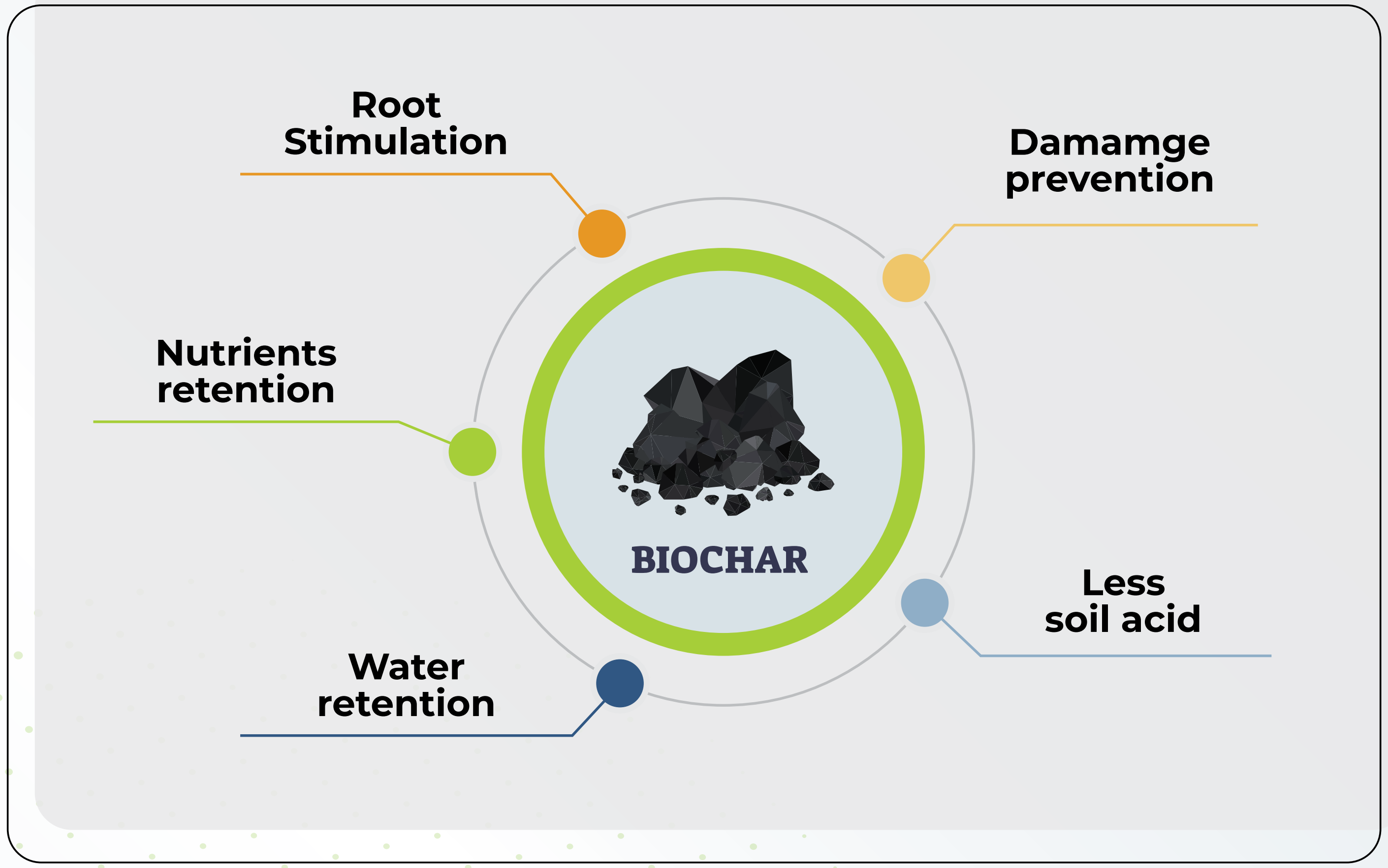
Stimulation of the root system.
Biochar is an optimal substrate for root growth too[1,13], capable of stimulating rooting both in number and biomass, allowing soil aeration and consequently the absorption increase of water and nutrients contained in the soil[3]. Furthermore, the presence of activated carbon in the rhizosphere can remove the phytotoxic exudates produced by the roots and reduce the presence of weeds, inducing a further decrease in the herbicides required[3].

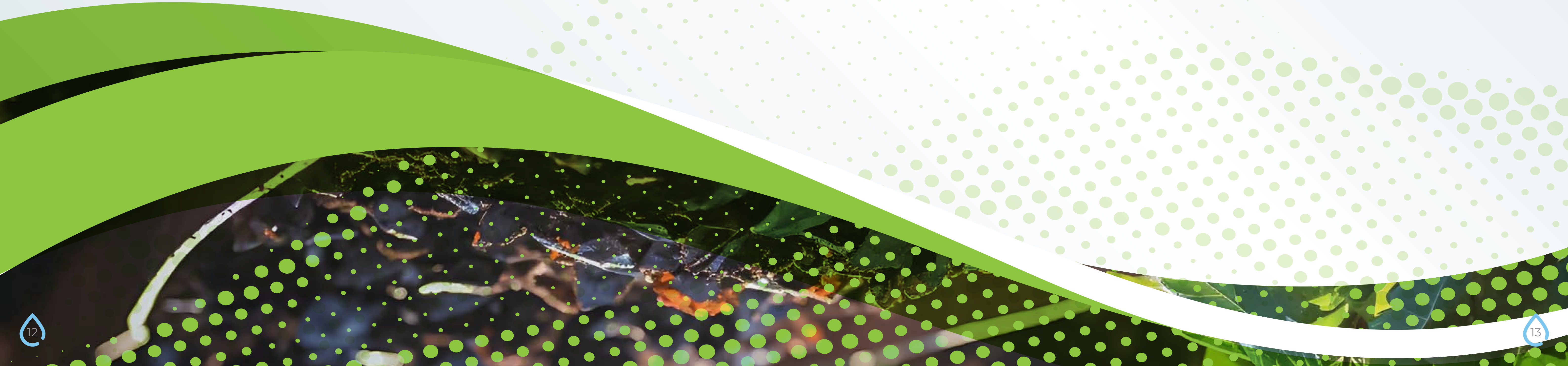
Support for biological control
Biochar is a protagonist in biological and integrated pest management, contributing to preserving from the damages caused by parasites and pathogens[14]. In the rhizosphere, the soil zone near the roots, Trichoderma sp. acts as bio-protectors by competing with pathogenic microorganisms and stimulating the strengthening of the plant's immune system[15]. Trichoderma can be applied to agricultural soils combined with biochar in the context of biological and/or integrated pest management to contrast fungal and bacterial infections and to decrease the attraction of vector insects.

Regarding the **physio-chemical properties** of soils, biochar can support:

Moisture conservation in arid ecosystems.
Biochar is a vegetable charcoal with high porosity, increases the content of available water (WHC - water holding capacity) within the soil, providing the ideal chemical-physical conditions for increasing productivity even in the driest ecosystems, such as those of the Mediterranean basin. Comparative studies between biochar, activated carbon, and pumice has shown that biochar produced from humus and wood has a higher water retention capacity and consequently increased conservation of water-soluble nutrients (p.e. Nitrate and Potassium), thus allowing a reduction of irrigation needs and plant water stress[16,3].

Limitation of soil acidification.
With a basic pH, biochar can also limit soil acidification, an increasingly frequent problem in agricultural soils subject to intensive exploitation and limited productivity. Lime is currently used to treat soil acidification, but recent studies have shown that using biochar makes it possible to reduce the amount of lime required with a consequent reduction in production costs[3].





4.

The environmental and socio-economic impacts

Biochar is an important ally for climate change mitigation, thanks to its ability to **incorporate carbon in a stable form into the soil**, sequestering 3 tons of CO_2 per ton produced.
This phenomenon occurs during the production process, where the carbon dioxide that would normally be released into the atmosphere during the decomposition of organic matter is trapped inside the compound in a stable form and is prevented its spreading into the atmosphere.
Recent studies have estimated that a 250-hectare farm using biochar with added mineral nitrogen (ammonium sulphate) as a crop amendment can sequester up to **1,900 tons of carbon** a year[17]. If this approach is applied on a large scale, European CO_2 emissions would be reduced by 9%[18], with incremental benefits for production yields and the implementation of the associated photosynthetic process. Therefore, it can be said that biochar is not only a carbon-neutral technique, with zero CO2 emissions, but also carbon negative, as it can contribute to reducing the total content of this gas from the atmosphere.

Thanks to its stable and porous clay-like structure, biochar helps reduce the frequency and amount of water needed for irrigation, promoting nutrient absorption and ion exchange. The main **environmental benefits** associated with the application of biochar in the field include:

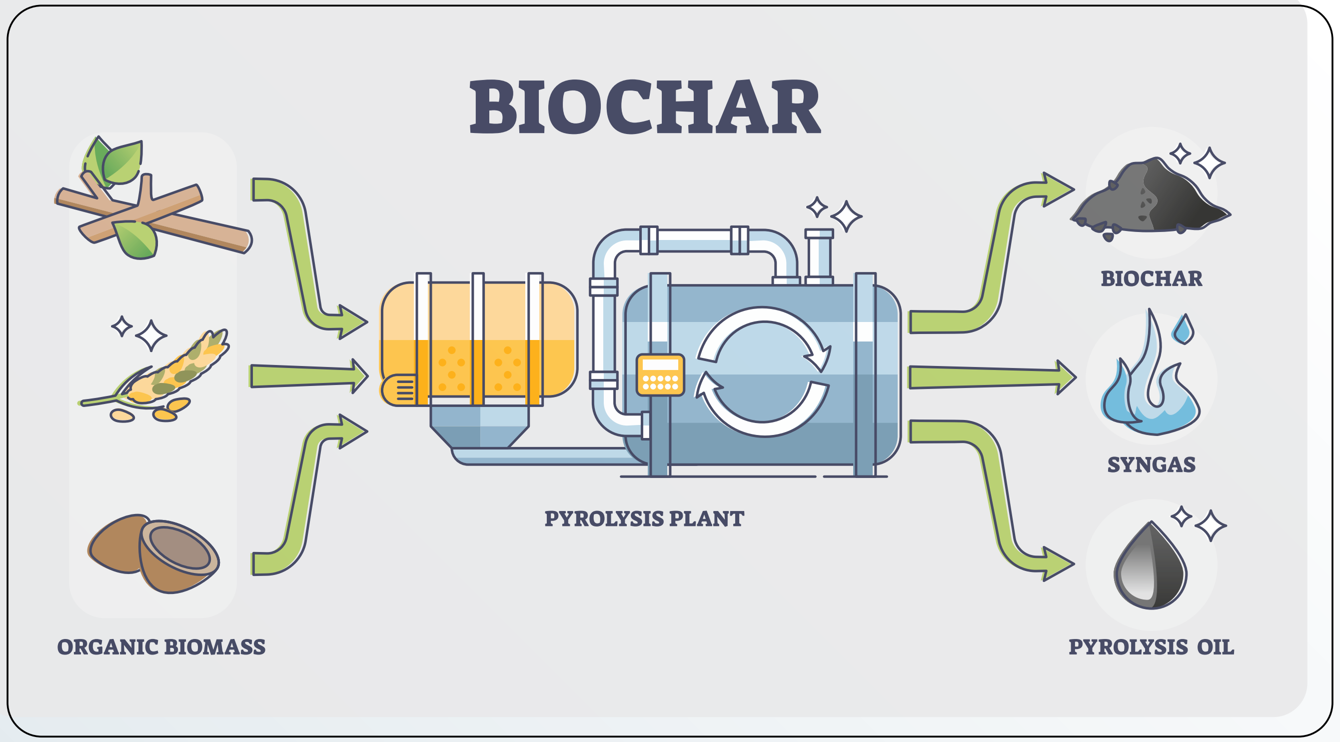
Limitation of nitrous oxide and ammonia emissions.
Using biochar as a soil improver favours more excellent nitrogen retention, ensuring the crops a superior absorption of nutrients and preserving the soil from leaching[19].
A recent study demonstrated an increase of 12% in nitrogen uptake in corn plants and a 26% increase in yield, obtaining better results than urea[20].

Thanks to its specific surface, biochar guarantees a high cationic and anion exchange capacity capable of making micro and macro-elements (ammonium and nitrate) available, reducing chemical and biological fertilisers and the consequent emissions of nitrous oxide and ammonia.
Nitrous oxide is a greenhouse gas with a 300 times greater impact than carbon dioxide on the atmosphere; it is released from the soil and ammonia as a by-product of chemical fertilisation.
The use of biochar reduces ammonia emissions from the agricultural origin by up to 19%, thanks to the combined limitation of synthetic nitrogenous fertilisers, other organic fertilisers and the spreading of sewage sludge, which would normally contribute to ammonia emissions by 15.2%, 3.9% and 0.5% respectively, again showing a positive effect in limiting greenhouse gases associated with climate change[21].

Pollutants absorption and bioremediation.
Another advantage associated with the use of biochar is the ability to immobilise various heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn)[22]. Biochar makes it possible to limit its bio-absorption by plants and consequently its absorption by humans[23]. For bioremediation of contaminated soils, biochar obtained at higher temperatures with a higher absorption capacity is preferred[24].

The use of biochar is promising from an environmental point of view but is associated with numerous advantages regarding economic sustainability[25].
The process production of biochar is one of the most sustainable, as it is based on **circular economy principles**: agricultural waste such as twigs, prunings, vines and other cellulosic materials, and sludge from wastewater and food industries are precious raw materials used in the pyrolytic process, converting disposal costs into an income element.
In fact, we must remember that the pyrolytic process, in addition to producing biochar, also allows the generation of **renewable energy** in the form of biofuel/syngas and **heat**, maximising technological investment costs[26]. This heat can be used to dry new biomass before the pyrolysis process takes place and if integrated into a local heating network, it enables a reduction in dependence and costs on fossil fuels.

Thanks to the reduction of the use of fertilisers, lime, and soil conditioner, with a parallel increase in yields, biochar qualifies as one of the most useful allies in agriculture, including the organic segment.
With an increase of 5.3% in organic cultivated area per year[27], this sector is driven by a growing demand; consumers prefer buying organic products, a percentage that is destined to increase in the future[28].



The activities associated with biochar production also entail some **social advantages**; the biochar production industry is a rapidly growing sector: the market is valued at 170.9 million US $ in 2020 and it is estimated that in the future, production will reach 587.7 million US $[29]. An increase of this entity will allow the employment in the industrial production of an ever-increasing number of skilled workers and technicians and the entire commercial-related industries.
Furthermore, at the agricultural level, the possibility of adding a single product in fields with multiple advantages allows farmers to save time and energy in fertilising the land and to be able to use their time to other activities, providing an important improvement in working conditions.

5.

Biochar practical indications

Dosages and methods of use

The dosage of biochar in the field requires a preliminary chemical-physical and biological characterisation of the soil[30] to formulate the correct administration based on the soil and crop type. Currently, the limited availability of experimental evidence does not allow the formulation of universal recommendations; the type of source material (forest, agro-industrial waste, organic waste) and the application of production processes, heterogeneous in terms of temperature, pressure, heating rate and duration generate different types of biochar. The composition of the starting raw material differing in the amount of hemicellulose, cellulose, lignin, and the thermal behaviour during pyrolysis are considered crucial factors for the biochar yield. High lignin contents ensure better process reactivity, stable carbon production and consequent effectiveness during agronomic applications.

Numerous studies have demonstrated the positive effects of biochar on crops administered with dosages within an extensive range between 5 and 50 tons per hectare.

As regards the frequency of application of biochar in the field, it has been observed that even single applications are able to provide positive effects, this is due to its ability to degrade very slowly in the soil, therefore unlike other synthetic fertilisers, biochar does not require to be applied with each crop.

Currently, the protocol is different for each use:

- **HORTICULTURE**: 3 m^3 / 1,000 m^2 in soil preparation, with basic fertilisation, at the beginning of the vegetable's vegetative cycle · 0.5 m^3 / 1,000 m^2 at the end of the vegetable's vegetative cycle, on crop residues, before Surface plowing for set-aside between two successive cycles.
- **FRUIT GROWING**: 10 m^3 / ha in soil preparation, with pre-planting fertilisation · 1 m^3 / ha In September - October as soon as the harvest is over.
- **WINE**: 13 m^3 / ha in soil preparation, with pre-planting fertilisation · 1.5 m^3 / ha in September - October as soon as the harvest is over.
- **OLIVE TREE**: 9 m^3 / ha in soil preparation, with basic fertilisation, at the beginning of the vegetative cycle · 1.5 m^3 / ha at Vegetative Recovery.
- **ARABLE CROPS**: 3 m^3 / ha in soil preparation, with basic fertilisation, at the beginning of the vegetative cycle. 0.5 m^3 / ha at the end of the vegetative cycle, on crop residues, before surface plowing for set-aside between two successive cycles.
- **FLORAL NURSERY**: 2% 10% by volume in the substrate formulation for sowing, transplanting and cultivation[31].

6.

Market and regulations: prospects and issues for the agricultural sector

Over the last decades, biochar has been affected by growing market interest, thanks to a broader knowledge of the chemical-physical properties and the advantages of developing numerous productive sectors. In European legislation, with EU directive 2019/2164[32], biochar is considered compliant with the objectives and principles of organic production as a fertiliser and soil improver, included in Annex I of Regulation (EC) No. 889/2008 and therefore admitted to the Community market[33].

However, the destination of biochar-based products does not adhere to the regulation of fertilising products (Fertilizing Products Regulation) for which each Member State reserves their classification[33]. Different compositions of the starting raw material and the application of different biochar production processes hold back market development due to standardisation, traceability, and approval difficulties.

In order to overcome these regulatory hurdles, the International Biochar Initiative (**IBI**) is promoting the development of a certification program, the European Biochar Certificate (**EBC**), to facilitate its commercialisation and safe and responsible use[25].

As the importance of biochar has increased, many counties have introduced similar laws to the IBI and EBC standards, while others still use biochar under the specifications of fertilisers and compost[25]. These industrial guidelines are voluntarily implemented; for this reason, in many cases, they are still unsatisfactory for completely regulating the biochar market.

The main issues related to the use of this practice rely on the **novelty** of the practice itself: it implies a still undefined and evolving market, characterized by variable and sustained prices due to a lack of balance between supply and demand. The limited knowledge of biochar production practices and its use by farmers themselves is reflected in a discontinuous production that is difficult to estimate in terms of annual production volumes.

In fact, the current production of biochar is an exclusive industrial prerogative requiring systems and technologies capable of processing large volumes of biomass and with control of the high temperatures of the process. Biochar for agronomic applications is available on the market in an extensive price range (from 90 to 5,000 US $/ton) depending on several factors, such as the degree of development of the economies in which the biochar is applied, the composition of the raw material, the production process and the type of cultivation for which it is destined[34].

Small-scale farm production is still minimal; there are limited pilot studies dedicated to producing biochar in the field. For example, small-scale pyrolytic plants are installed on farms in Sweden and other Nordic countries to generate heat to support operational management costs and produce amendments for agronomic uses[44] .

In agreement with these cases, from a plant sized at 50kW the annual production of biochar obtainable is around 26 tons, suggesting the consideration that the implementation of pyrolytic plants “in field” could be exploited by small agricultural realities as a form of diversification of the income model[35].

If it is impossible to apply the technology in a capillary way, studies indicate numerous potential advantages from producing biochar at a rural level, also through logics based on scale economies for the optimisation of process costs. Access to low-cost and locally available raw biomass near the production plants (within 50-200 km) reduces the impact of biomass logistics costs and supports the profitability of the production model[26]. But we have to consider the variability in soil types and environmental conditions, which is not a trivial task in order to predict the fate and effect of biochar on soil. The current understanding of the overall **effects** of biochar on soil and soil biota and their mutual interactions is not clear because biochar can have positive, negative, or neutral effects. These mixed findings clearly illustrate that the complex interactions and resulting effects of biochar on soil biota have been inadequately studied. Conclusions drawn from mainstream biochar-promoting studies may be misleading given that biochar is perceived as a positive tool for improving soil quality without considering the overall picture, and possible negative effects are usually overlooked at all levels.

Another serious issue related to the sustainable use of biochar concerns the necessity of **optimizing** the rate of the repeated and cumulative application of biochar to the environment, where it may remain for decades or even centuries, as well as further exploring the consequences of biochar ageing in soil and the related effects on the soil environment.

The long-term effects of these phenomena are not yet fully understood.

For preventing the critical adverse effects of biochar, rational, detailed, and precise guidelines should be developed specifying the information (on biochar, soil, and environmental conditions) that needs to be known/recorded and the criteria that need to be fulfilled (with respect to the intended effects of biochar on the soil) for the large-scale application of biochar to soils. This information may include soil properties and types, climatic conditions, water regime, content and supply (fertilization) of nutrients and other substances (e.g., pesticides, contaminating substances), type and cultivation method of the crop to which biochar is applied, prediction and modelling of the time-scheduling of the biochar's effect to achieve a targeted effect on treated areas, and side effects that are minimized because of well-known risk levels. However, such an approach requires an ongoing comprehensive study of soil additives and agro-management's multifactor impact on the soil-organism-plant-environment system.

On the other side, there might be new perspectives for the biochar market development, like the opportunity to combine its use with **carbon credits**[36], i.e. units equivalent to the removal of one ton of CO2 from the atmosphere. In the modern industrial context, with a view to environmental sustainability, companies more frequently access **certified carbon credits**, a financial instrument for virtuously offsetting the residual emissions of greenhouse gases generated during production in the petrochemical, steel, concrete, and aviation fields. Biochar can also be included within the carbon credit market, thanks to its ability to sequester and store carbon in a stable form up to about 3 tons per single ton of biochar produced, thus generating 3 carbon credits per single ton of biochar produced[31]. Currently, the global carbon credit market is expanding rapidly, with costs settling at €20/t CO_2, but presumably, in a few years voluntary credits will go towards €50/t CO_2, values really interesting in view of expanding the uses of biochar[37].

7.

Bioeconomy and resource recovery in the RESIDUE project context

Reclaimed wastewater use in agriculture.

The world population growth, the consequent impacts on human and the environment health demand a fast-moving transition towards a low-emission and zero-waste economy.
Clean and sustainable use of water is one of the leading priorities for a sustainable society called upon to counteract water depletion and climate change.

Agriculture is the production sector that requires more water resources and in some areas, uses more than 80% of the available water, often resulting in significant water wastage[38].
One of the many solutions to solve water shortage is the reuse of treated wastewater (WW), as well as water savings. The Mediterranean is the most affected area by these phenomena, where countries often provide incentives and investments to counteract surface water depletion.
Despite this high potential, the number of companies involved in the sale and installation of domestic WW treatment plants is minimal, therefore a big part of the treatments takes place in industrial WW treatment plants.
Ordinary WW treatment requires mechanical, chemical, and biological processes to eliminate pollutants from the water.
After careful quality controls, treated WW and sludge can be discharged into the environment.

The Urban Wastewater Treatment Directive (91/271/EEC)[39] defines urban wastewater as "domestic water or the mixture of domestic wastewater with industrial wastewater and/or run-off rainwater". This Directive, concerning urban wastewater collection, treatment and discharge, demands European countries the reusing of treated wastewater whenever appropriate to reduce the withdrawal of surface and groundwater from natural resources. The reuse of WW is a crucial issue in EU water policy[40] as an alternative water source in regions with obvious water scarcity issues. As stated by the European Union in 2015, "the reuse

of treated WW under safe and cost-effective conditions is a valuable but underused mean of increasing water supply and relieving pressure on over-exploited resources”.
The regulation adopted by the European Parliament and the Council on 13 May 2020[41] introduced minimum requirements for the reuse of water for irrigation purposes in agriculture. In this context, the reuse of WW has been acknowledged as one of the priority solutions with lower environmental impact than alternative water supply measures, such as water transfers or desalination. These guidelines are also part of the European New Green Deal which aims to reduce pollution from excess nutrients through a strategy called “from producer to consumer”. Water reuse and nutrient management are among the actions promoted by the new Circular Economy Plan[42].
In this context, the RESIDUE project aims to suggest new strategies and technologies to improve soil fertility, preservation of agricultural land and reuse of wastewater in arid areas.

The sewage sludge use in agriculture.

Sewage Sludge (SS) is one of the leading products derived from WW treatment and further growth is expected in the coming years as a result of the Urban Wastewater directive as well as the number of households connected to sewers is increasing the quantity of sewage sludge requiring disposal.
The disposal of sludges represents a relevant part of the operating cost of a WW treatment plant, contributing up to 50% of the total cost. Therefore, a process of dehydration is usually applied, increasing the dry content typically to a percentage between 20-25 % and reducing the amount of sludge release[42]. The reuse of SS is a crucial element of sustainable management of the integrated water system. It is an essential resource in terms of the **circular economy** for the production of electricity from biogas or as biological raw material for the production of biomethane, eco-fertilisers such as biochar, phosphorus and nitrogen, that can be reused in the most advanced industrial sectors and agriculture[42].

The Sewage Sludge Directive (86/278/EEC)[43] seeks to encourage the use of SS in agriculture and to govern its use in such a way as to prevent harmful effects on soil, vegetation, animals and man. According to this Directive, “sludge” is defined as “residual sludge from sewage plants treating domestic or urban wastewaters and from other sewage plants treating wastewaters of a composition similar to domestic and urban wastewater; residual sludge from septic tanks and other similar installations for the treatment of sewage; residual sludge from sewage plants other than those referred above”.
The Directive prohibits the use of untreated sludge on agricultural land, regardless of its source, unless it is injected or incorporated into the soil. It also establishes the limit values for concentrations of heavy metals and microbial parameters (Salmonella spp. and Escherichia Coli) in SS intended for agricultural use.

SS obtained from a biological process that meets strict qualitative requirements, also called biosolids, can be used in agriculture as an organic fertiliser due to its high content of macro and micronutrients which are essential for the growth of crops.
The significant component of biosolids is organic matter, which forms an average of 50% to 60% of the dry solids content, nutrients deemed essential in crop nutrition (25.5% such as nitrogen, phosphorus, and potassium, but also small quantities of copper, magnesium, and zinc). Liquid sludge that has not been treated as well as processed sludge that has been dewatered release nitrogen slowly, providing benefits to crops over a considerable amount of time. In fact, anaerobically digested sludge contains a high concentration of ammonia, which plants rapidly absorb; as a result, it can be used as a nutrient-rich fertiliser. The organic matter content of sludge can improve soil’s physical, chemical and biological properties, resulting in improved cultivation and aquiferous capacity, particularly when applied in the form of dewatered sludge cake. In addition, organic nitrogen in sludge is far less likely than chemical nitrogen fertiliser to pollute ground water[46].

However, they can also contain potentially toxic elements such as metals and pathogens, but these contaminants must be reduced under limit values established by Europe and the Member States to ensure the safety of biosolids applications[44].
One of the processes that can be applied on SS to reduce the contaminant loading, is **composting**. Composting provides a cost-effective way to stabilise the material by enhancing microbial activity and reducing biodegradable organic contaminants’ concentration. It is an aerobic process in which the biodegradable part is degraded to stable humic components with the help of microbes. Compared to pure SS, the finished compost product contains a high level of degraded organic matter and a low amount of harmful metals and pathogens. However, little is known on whether the composting process achieves the desired

extent of contaminant degradation or entrapment to reduce their availability for plant uptake[45].

In this context, the **RESIDUE project** aims to find new agronomic strategies and approaches using sewage sludge from wastewater to improve soil fertility in areas interested in leaching and drought.

Future prospects on biochar and wastewater/ sewage sludge treatmentg

The disposal and reuse of SS is identified as a future problem concerning wastes. The total amount of sludge generated worldwide has increased dramatically, and this trend is expected to rise significantly in the years to come. The management of this waste is still a challenge, considering that some amounts of sludge are recycled during wastewater treatment installation to optimize operations, yet large quantities of SS must still be disposed of and managed. The objectives of modern technologies for sludge treatment are: reducing weight and volume, destroying pathogenic microorganisms, removing foul/offensive smells and reducing volatile solid contents for safer disposal. The number and types of technological processes of sludge treatment not only depend on the nature and amount of processed sludge but also depend on the sewage sludge's final management method[48]. The current circular economy strategy in WW management is looking for new ways to reuse sewage sludge. Among these, we consider thermal treatment, such as incineration, gasification, hydrothermal carbonation (HTC) and pyrolysis, which are suitable solutions for sludge disposal. There are two routes: the first is to incinerate the sludge to produce energy, the second is to transform it into a new product for agricultural use. The latter route represents a research challenge, with a focus on pyrolysis products, especially biochar, which can be the main result of sludge pyrolysis, becoming a relevant application in WW management and agriculture. Consequently, it is essential to define its characteristics and compare it with biochar from other biomass sources to obtain future certification for agricultural use as a soil amendment. The carbonisation of SS is one of the most promising ways of reusing it in agriculture to date, avoiding environmental problems with pathogens, organic pollutants and even PFAS (perfluorinated alkylated substances). The biggest problem with its use is the heavy metal loads, which in most cases are not removed during carbonisation and accumulate in the final product due to loss of material. One way to avoid critical concentrations and immobilise heavy metals is to co-pyrolyse sludge with other biomass. In this way, different percentages of sewage sludge and organic residues are used to create various types of biochar that can meet different soil requirements.

Biochar from SS (also called SSB-sewage sludge biochar) can be applied in fields as a soil amendment to improve physio-chemical properties and at the same time increase carbon sequestration and reduction of greenhouse gas emissions. One of the major advantages in the use of SSB is that a large part of the contaminants presents in the SS is eliminated during the pyrolysis process of conversion; furthermore, several studies have demonstrated that pyrolysis fully eliminates microbial pathogens and stabilises heavy metals in SSB, generating a good quality biochar[45]. Another benefit of using SS as a feedstock to produce biochar is that it is comparatively less expensive than other sources such as agricultural and wood waste, which contribute to push the market towards a more sustainable approach of circular economy[45].

SSB thus formed, can be used for another important application in advantage to soil safety, capitalising on the biochar adsorbent properties in water and WW to remove various contaminants. Its application mostly involves the removal of heavy metals, organic pollutants, nitrogen, and phosphorus from wastewaters. In particular, biochar prepared from SS adsorbed approximately 70% of Cr^{3+} from the aqueous solution reducing the total quantity of heavy metal[47].

In this context, the RESIDUE project aims to improve the production of biochar from sewage sludge and other organic plant residues, generating a 'compochar'. CompoCharTM, a biochar-based growing substrate, can be produced anywhere from local organic waste such as wood waste and composted SS, a renewable and nutrient-rich raw material. CompoChar reduces atmospheric CO_2 and helps combat climate change. Dr. Nadav

Ziv, the CEO and R&D manager of Earth Biochar ltd. in Israel, describes that for this process, municipal SS undergoes a complete composting process. The homogenous SS compost is mixed with shredded wood waste and pyrolysed at 550° C in a continuous pyrolysis system. The resulting product is characterised for its soil-free growing medium properties and after measuring many other characteristics (i.e. hazardous elements concentration, water retention curve, electric conductivity, pH), it can state that pyrolysis is a promising method to significantly reduce the risks of SS compost and improve its value as a soilless growing medium. In this way, after the improvement of the process, it will be possible to utilise biochar treated wastewater to irrigate fields in all the Mediterranean region, that will be increasingly interested by drought and water scarcity in the following years.

The findings from the RESIDUE experiments underscore the significance of organic amendments such as composted biosolids and pyrolyzed composted biosolids (i.e., biochar) in mitigating contaminants bioavailability in agricultural soils, thereby bolstering food safety and overall product quality. Our data indicate that biochar is a highly effective sorbent, surpassing composted biosolids probably due to higher surface area and sorptive sights. Strategically incorporating 1.5% (w/w) of biochar into the soil can substantially decrease contaminants' bioavailability by over 80%, while composted biosolids offer a reduction of around 40%. These figures highlight the potency of composted biosolids and specifically biochar in soil remediation efforts. In addition, leaching experiments have shown that biochar has the potential to increase the retention of pharmaceuticals, such as carbamazepine, in treated wastewater irrigation, thereby reducing the risk of groundwater contamination and ensuring water safety. Labelled compound studies further support the efficiency of biochar, with a significant reduction in bioavailability observed in soils amended with co-composted biochar (70% compost, 30% biochar). Overall, the use of biochar and composted biosolids not only enhances food safety but also enriches soil fertility by introducing valuable nutrients while simultaneously curbing the bioavailability of undesirable compounds. This dual benefit underscores the potential of organic amendments in sustainable agriculture practices.

Bibliography

(1) Lehmann, J., Joseph, S., Eds.; Earthscan Biochar for Environmental Management: Science and Technology; London ; Sterling, VA, 2009.

(2) EBC (2012-2022) “European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.”; Version 10.2 from 8th Dec 2022; Carbon Standards International (CSI), Frick, Switzerland. (http://european-biochar.org).

(3) Lehmann, J.; Rillig, M. C.; Thies, J.; Masiello, C. A.; Hockaday, W. C.; Crowley, D. Biochar Effects on Soil Biota – A Review. Soil Biol. Biochem. 2011, 43 (9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

(4) Bezerra, J.; Turnhout, E.; Vasquez, I. M.; Rittl, T. F.; Arts, B.; Kuyper, T. W. The Promises of the Amazonian Soil: Shifts in Discourses of Terra Preta and Biochar. J. Environ. Policy Plan. 2019, 21 (5), 623–635. https://doi.org/10.1080/1523908X.2016.1269644.

(5) What are the air emissions of burning wood? – Wood Energy. https://wood-energy.extension.org/what-are-the-air-emissions-of-burning-wood/ (accessed 2023-01-03).

(6) Artiola, J.; Wardell, L. Guide to Making and Using Biochar for Gardens in Southern Arizona. 2017, AZ1752.

(7) Biochar Production Technologies. biochar-international. https://biochar-international.org/biochar-production-technologies/ (accessed 2023-01-23).

(8) Shankar Tumuluru, J.; Sokhansanj, S.; Hess, J. R.; Wright, C. T.; Boardman, R. D. REVIEW: A Review on Biomass Torrefaction Process and Product Properties for Energy Applications. Ind. Biotechnol. 2011, 7 (5), 384–401. https://doi.org/10.1089/ind.2011.7.384.

(9) Agricoltura - Arpa per le imprese. ARPA Lombardia. https://www.arpalombardia.it:443/Pages/Arpa-per-le-imprese/Autorizzazioni-e-Controlli/Agricoltura.aspx (accessed 2023-01-03).

(10) Menegat, S.; Ledo, A.; Tirado, R. Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture. Sci. Rep. 2022, 12 (1), 14490. https://doi.org/10.1038/s41598-022-18773-w.

(11) Solomon, S., Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Intergovernmental Panel on Climate Change, Eds.; Cambridge University Press: Cambridge ; New York, 2007.

(12) Ding, Y.; Liu, Y.; Liu, S.; Li, Z.; Tan, X.; Huang, X.; Zeng, G.; Zhou, L.; Zheng, B. Biochar to Improve Soil Fertility. A Review. Agron. Sustain. Dev. 2016, 36 (2), 36. https://doi.org/10.1007/s13593-016-0372-z.

(13) Liang, B.; Lehmann, J.; Sohi, S. P.; Thies, J. E.; O’Neill, B.; Trujillo, L.; Gaunt, J.; Solomon, D.; Grossman, J.; Neves, E. G.; Luizão, F. J. Black Carbon Affects the Cycling of Non-Black Carbon in Soil. Org. Geochem. 2010, 41 (2), 206–213. https://doi.org/10.1016/j.orggeochem.2009.09.007.

(14) Bonanomi, G.; Ippolito, F.; Scala, F. A “Black” Future for Plant Pathology? Biochar as a New Soil Amendment for Controlling Plant Diseases. J. Plant Pathol. 2015, 97, 223–234. https://doi.org/10.4454/jpp.v97i2.3381.

(15) Guerrieri, E.; Lingua, G.; Digilio, M. C.; Massa, N.; Berta, G. Do Interactions between Plant Roots and the Rhizosphere Affect Parasitoid Behaviour? Ecol. Entomol. 2004, 29 (6), 753–756. https://doi.org/10.1111/j.0307-6946.2004.00644.x.

(16) Pietikäinen, J.; Kiikkilä, O.; Fritze, H. Charcoal as a Habitat for Microbes and Its Effect on the Microbial Community of the Underlying Humus. Oikos 2000, 89, 231–242. https://doi.org/10.1034/j.1600-0706.2000.890203.x.

(17) Https://Www.Ichar.Org/Content.Php?Page=136.

(18) Glaser, B.; Parr, M.; Braun, C.; Kopolo, G. Biochar Is Carbon Negative. Nat. Geosci. 2009, 2 (1), 2–2. https://doi.org/10.1038/ngeo395.

(19) Yanai, Y.; Toyota, K.; Okazaki, M. Effects of Charcoal Addition on N2O Emissions from Soil Resulting from Rewetting Air-Dried Soil in Short-Term Laboratory Experiments. Soil Sci. Plant Nutr. 2007, 53 (2), 181–188. https://doi.org/10.1111/j.1747-0765.2007.00123.x.

(20) Ndoung, O. C. N.; Figueiredo, C. C. de; Ramos, M. L. G. A Scoping Review on Biochar-Based Fertilizers: Enrichment Techniques and Agro-Environmental Application. Heliyon 2021, 7 (12), e08473. https://doi.org/10.1016/j.heliyon.2021.e08473.

(21) 1_Agricoltura Finale.Pdf. https://www.isprambiente.gov.it/files/pubblicazioni/statoambiente/annuario-2016/1_Agricoltura%20finale.pdf (accessed 2023-01-03).

(22) Wang, H.; Zhang, X. Biochar for the Remediation of Soils Contaminated with Potentially Toxic Elements.

(23) Wang, J.; Shi, L.; Zhai, L.; Zhang, H.; Wang, S.; Zou, J.; Shen, Z.; Lian, C.; Chen, Y. Analysis of the Long-Term Effectiveness of Biochar Immobilization Remediation on Heavy Metal Contaminated Soil and the Potential Environmental Factors Weakening the Remediation Effect: A Review. Ecotoxicol. Environ. Saf. 2021, 207, 111261. https://doi.org/10.1016/j.ecoenv.2020.111261.

(24) Uchimiya, M.; Wartelle, L. H.; Lima, I. M.; Klasson, K. T. Sorption of Deisopropylatrazine on Broiler Litter Biochars. J. Agric. Food Chem. 2010, 58 (23), 12350–12356. https://doi.org/10.1021/jf102152q.

(25) Carvalho, J.; Nascimento, L.; Soares, M.; Valério, N.; Ribeiro, A.; Faria, L.; Silva, A.; Pacheco, N.; Araújo, J.; Vilarinho, C. Life Cycle Assessment (LCA) of Biochar Production from a Circular Economy Perspective. Processes 2022, 10 (12), 2684. https://doi.org/10.3390/pr10122684.

(26) Homagain, K.; Shahi, C.; Luckai, N.; Sharma, M. Life Cycle Cost and Economic Assessment of Biochar-Based Bioenergy Production and Biochar Land Application in Northwestern Ontario, Canada. For. Ecosyst. 2016, 3 (1), 21. https://doi.org/10.1186/s40663-016-0081-8.

(27) FiBL, R. I. of O. A. Exceptional growth of the European organic market 2020 – Organic market reaches 52 billion euros and organic farmland 17 million hectares in 2020. https://www.fibl.org/en/info-centre/news/exceptional-growth-of-the-european-organic-market-2020 (accessed 2023-01-05).

(28) Moreno. Continua a crescere la richiesta di prodotti Bio: un mercato che vale 40,7 Mld di € a livello europeo. beverfood.com. https://www.beverfood.com/a-crescere-richiesta-prodotti-bio-mercato-vale-40-7-mld-a-livello-europeo-wd/ (accessed 2023-01-05).

(29) Biochar Market Size, Trends 2030: Industry Forecast. Allied Market Research. https://www.alliedmarketresearch.com/biochar-market-A11816 (accessed 2023-01-03).

(30) Major, J. Guidelines on Practical Aspects of Biochar Application to Field Soil in Various Soil Management Systems.

(31) Onyx, W. Dosaggi e modalità d’impiego del biochar.

(32) REGOLAMENTO DI ESECUZIONE (UE) 2019/2164 DELLA COMMISSIONEpdf. https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:32019R2164&from=IT (accessed 2023-01-05).

(33) Štrubelj, L. Waste, Fertilising Product, or Something Else? EU Regulation of Biochar. J. Environ. Law 2022, 34 (3), 529–540. https://doi.org/10.1093/jel/eqac013.

(34) Osti, S. Biochar, un ammendante che sequestra la CO2. Terra e Vita. https://terraevita.edagricole.it/fertilizzanti-concimi/biochar-ammendante-sequestra-co2/ (accessed 2023-01-05).

(35) Azzi, E. S.; Karltun, E.; Sundberg, C. Small-Scale Biochar Production on Swedish Farms: A Model for Estimating Potential, Variability, and Environmental Performance. J. Clean. Prod. 2021, 280, 124873. https://doi.org/10.1016/j.jclepro.2020.124873.

(36) Crediti_di_Carbonio_ITA_.Pdf. https://carbonsink.it/wp-content/uploads/2022/02/Crediti_di_Carbonio_ITA_.pdf (accessed 2023-01-23).

(37) Isonio, E. Biochar, il boom è dietro l’angolo: +164% nei prossimi 5 anni. Re Soil Foundation. https://resoilfoundation.org/economia-finanza/biochar-crescita-valore-mercato/ (accessed 2023-01-23).

(38) Pisante, M.; Acutis, M.; Anastasio, A.; Battilani, P.; Bindi, M.; D'Andria, R.; D'Urso, G.; Pascale, S. D.; Draisci, R.; Frascarelli, A.; Frisio, D.; Grignani, C.; Inglese, P.; Lanciotti, R.; Mastrorilli, M.; Mosca, G.; Neviani, E.; Perniola, M.; Schirone, M.; Suzzi, G.; Tofalo, R.; Tonelli, C.; Torriani, S.; Visciano, P. Water in agriculture: sustainable use of the irrigation practices - L'acqua in agricoltura: gestione sostenibile della pratica irrigua. 2015, Edagricole-Edizioni Agric.

(39) Urban Waste Water Directive - Environment - European Commission. https://ec.europa.eu/environment/water/water-urbanwaste/legislation/directive_en.htm (accessed 2023-02-16).

(40) Water Reuse - Environment - European Commission. https://ec.europa.eu/environment/water/reuse.htm (accessed 2023-02-16).

(41) European Commission. Regulation 2020/741; 2016. https://doi.org/10.5040/9781782258674.

(42) Circular economy action plan. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed 2023-02-16).

(43) Sewage Sludge Directive 86/278/EEC. https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:31986L0278&from=EN (accessed 2023-02-02).

(44) BIOSOLIDS PRODUCTION. efar. https://www.efar.be/biosolid-production/ (accessed 2023-02-16).

(45) Ghorbani, M.; Konvalina, P.; Walkiewicz, A.; Neugschwandtner, R. W.; Kopecký, M.; Zamanian, K.; Chen, W.-H.; Bucur, D. Feasibility of Biochar Derived from Sewage Sludge to Promote Sustainable Agriculture and Mitigate GHG Emissions—A Review. Int. J. Environ. Res. Public. Health 2022, 19 (19), 12983. https://doi.org/10.3390/ijerph191912983.

(46) Usman, K.; Khan, S.; Ghulam, S.; Khan, M. U.; Khan, N.; Khan, M. A.; Khalil, S. K. Sewage Sludge: An Important Biological Resource for Sustainable Agriculture and Its Environmental Implications. 2012, 2012. https://doi.org/10.4236/ajps.2012.312209.

(47) Xiang, W.; Zhang, X.; Chen, J.; Zou, W.; He, F.; Hu, X.; Tsang, D. C. W.; Ok, Y. S.; Gao, B. Biochar Technology in Wastewater Treatment: A Critical Review. Chemosphere 2020, 252, 126539. https://doi.org/10.1016/j.chemosphere.2020.126539.

(48) Elena Goldan, Valentin Nedeff, Narcis Barsan, Mihaela Culea, Claudia Tomozei, Mirela Panainte-Lehadus and Emilian Mosnegutu, Evaluation of the Use of Sewage Sludge Biochar as a Soil Amendment—A Review, Sustainability 2022, 14(9), 5309; https://doi.org/10.3390/su14095309

Colophon

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