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# Industrial production of activated carbon using circular bioeconomy principles: Case study from a Romanian company

Sebestyen Tihamer Tibor[a,b], Carlos A. Grande[c,d,*]

[a] Babes-Bolyai University, Faculty of Geography, Department of Geography in Hungarian, Clinicilor Street 5-7, Cluj-Napoca, Romania
[b] Explocom GK Ltd, Filiaș 102/D, Cristuru Secuiesc, 535400, Romania
[c] SINTEF AS, Forskningsveien 1, 0373, Oslo, Norway
[d] King Abdullah University of Science and Technology, Division of Physical Sciences and Engineering, Advanced Membranes & Porous Materials Center, Thuwal, 23955-6900, Saudi Arabia

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ABSTRACT

This work discloses an industrial multi-ton scale methodology implemented by a Romanian company (Explocom GK) to use bio-wastes to produce biochar, demonstrating a case of bio-economy circularity associated with economic growth. The pyrolysis process was able to produce ~20%w of high-quality biochar (550 $m^2$/g) starting from forest-based and agricultural wastes. A fraction of ~60%w is converted into condensates, including wood vinegar, wood tar, alcohol, etc. that can be recovered and purified because of the large scale of the process. The energy contained in the volatile syngas produced (~20%w) is stored and used instead of fossil fuels for heating the pyrolysis reactor. Some of this syngas and wood vinegar can also be used to activate a fraction of the biochar into high-quality activated carbon (value of activated carbon/value of biochar >3, depending on the market and required properties). The transformation of a fraction of the produced biochar into activated carbon increases the overall profitability of the plant while manufacturing a product that does not use fossil fuels or chemicals for activation. This material locally produced can also reduce emissions from transport of activated carbons currently exported from other continents.

## 1. Introduction

Biochar is a carbon-rich material obtained from thermal conversion of biomass. Biochar is the same product as charcoal; the different terminology aims to differentiate its uses. While charcoal is commercialized for heating and cooking (being commonly associated to barbequing), biochar is suitable to retain carbon in soil, consequently eliminating $CO_2$ from the troposphere (Das et al., 2020). Carbon retention can be improved further by using alkali metals (Nan et al., 2020). Biochar is a soil ameliorant (bio-fertilizer) that can be used as a partial alternative, or combined, with conventional fertilizer (produced via usage of fossil fuels) and pesticides that are commonly used on several Mha of arable land (Kizito et al., 2019).

Biochar can be produced from specific feedstock like logwoods, coconut shells or short rotation crops (SRCs). In recent years, the "bio-waste" to biochar approach presents itself as an exceptional negative emissions technology providing multiple common goods like selective adsorbents at affordable cost (Jung et al., 2019). Biochar samples were produced from waste woods originated from forest-based industries, as well as from agriculture residues, such as straw, corn cob, pruning residuals from vineyard and orchards, solid bio-waste from municipal waste management activities, etc. and used in many different areas (Nanda et al., 2016; Wijitkosum and Jiwnok, 2019) like removal of heavy metals (Zhao et al., 2019). Some of the benefits of using bio-wastes for producing biochar are:

(a) restoration of soil carbon and water conservation capacities (Cazotti Tanure et al., 2019),
(b) increased crops yields (Kalus et al., 2019),
(c) climate change mitigation (Wang et al., 2020b).

These benefits are still lacking a holistic and coherent cross-sectoral policy approach to fully exploit the potential of biochar (Verde and Chiaramonti, 2021) and to maximize the environmental benefits of the different approaches. The IPCC declared that the use of biochar is an important strategic tool in the fight against global warming, stating

* Corresponding author. SINTEF AS, Forskningsveien 1, 0373, Oslo, Norway.
*E-mail address:* carlos.grande@kaust.edu.sa (C.A. Grande).

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"biochar is the best option for atmospheric carbon sequestration" ( 2018de Coninck and Revi,). The EC Green Deal confirmed this statement with the EU Regulation 2019/2164, declaring that biochar complies with the objective and principles of organic production in the EU's agriculture sector (European Commission, 2008, European Commission, 2020). Indeed, biochar comply with EU objectives of generating circular economy cycles from waste streams (Tagliaferro et al., 2020), even for streams that are difficult to treat like sewage sludges (Bolognesi et al., 2021).

In South-East Europe (SEE) countries, estimations suggest that there are over 30 Mton/year agricultural crops and solid residuals producing significant $CO_2$ emissions, especially by landfilling which is still practiced in non-EU countries (Wietschel et al., 2019). In Romania, the total agriculture biomass feedstock is estimated to be ~10 Mton/year, with an expected growth of 30% by 2030. Romania together with Bulgaria and Italy have the highest growth of agriculture biomass feedstock in Europe (Wietschel et al., 2019).

The market uptake capacity for biochar in agriculture sector in SEE is estimated over 60,000 ton/year (Masek et al., 2019). According to the international market research prognosis, the Compound Annual Growth Rate (CAGR) of biochar production will be 16,45% and this growth will continue until 2030 in the EU and EFTA countries (Ohra-aho et al., 2020).

The mismatch between the availability of residues and the required amount of biochar allows us to think about the possibility to extend the range of products from bio-wastes. In this regard, the production of high-performance activated carbon from biochar offers an extraordinary platform that is considered as a bio-innovator technology for many industrial branches like in remediation applications (Wang et al., 2020) with proven benefits in different and diverse countries, like Tanzania (Hansson et al., 2021). In Romania (~20 million inhabitants), the estimated market demand for activated carbon is 35–40 kt per year, with a market increase of ~10% per year (Nutriman project, 2021).

Activated carbon is a very flexible product with applications in multiple and very diverse economic and social sectors. Moreover, a variety of composite materials using activated carbon can be obtained

**Table 1**
Specific markets, applications and benefits of activated carbon and biochar.

| Product | Market | Sub-sector | Grade/Specs | Main benefits and use examples |
|---|---|---|---|---|
| Biochar | Agriculture | Crop growth<br>Livestock breeding | Low-middle range quality, granulated powdered, surface area lower than 500 $m^2/g$ | Soil stabilizer, $CO_2$ sequestration, increase soil permeability and porosity (Das et al., 2020), increase water retention, stabilize soil contamination (Wang et al., 2020), and reduce erosion, accelerate humus formation (Latawiek et al., 2017).<br>Facilitate livestock feeding (Hwang et al., 2018; Sánchez-Monedero et al., 2019) and management of manure (Man et al., 2021; Schmidt et al., 2019). |
| Activated carbon | Food and beverages | Sweeteners<br>Beverages<br>Soft drinks<br>Tobacco | Mid-range quality activated carbon, surface area >700 $m^2/g$ with microporous surface | Elimination of organic odors (Bertone et al., 2018).<br>Ultrapure water production, cleaning (Narzari et al., 2015) and washing in the production lines. |
| | Chemicals | Oil & gas<br>Painting, coatings<br>Gas activation<br>Refineries<br>High-added value | Granular activated carbon, Middle-high range quality activated carbons, surface area >800 $m^2/g$ with microporous surface | Filtration systems (Razmi et al., 2019), cleaning and washing processes, decoloration (Rawat and Singh, 2018), removal of contaminants like humic acids (Shankar et al., 2017), chlorobenzenes (Zhang et al., 2018), erythromycins (Muter et al., 2019), organic compounds and VOCs (Xiang et al., 2020; Rajabi et al., 2021; Zhang et al., 2021), BTEX (Sung et al., 2021), CODs ( Khurshid et al., 2021), etc.<br>Removal of inorganic vapors and acid gases (Di Stasi et al., 2019) and heavy metals (Gupta et al., 2020). Use as catalysts/catalyst carrier (Adarsh et al., 2020). |
| | Metallurgy | Metal recovery<br>Metal production | Granular activated carbon in most cases. Meso and micropores, depending on application | Metal extraction (Zhou et al., 2021), metal finishing, purification of electroplating solutions (Wang et al., 2020; Biswas et al., 2020). Discharge of metal ions (Zhang et al., 2020). Removal of selected metal cations (Lin et al., 2020) and inorganic vapors (Amusat et al., 2021). |
| | Water treatment | Drinking water<br>Wastewater management<br>Environmental remediation<br>Waste, ballast, mine and landfill | All kind of ranges depending on application. Shape tailored to application. Cost-efficient and environmentally friendly materials. | Filtration systems (Jayakumar et al., 2021; Kang et al., 2019), cleaning and washing processes (Xie et al., 2015; Lam et al., 2020), selective adsorption of contaminants (organic and inorganic) in liquid phase (Zhang et al., 2019; Bandara et al., 2020; Yi et al., 2020) and gas phase (Xiang et al., 2020), wastewater treatment ( Enaime et al., 2020; Qambrani et al., 2017). |
| | Defense | Collective protection<br>Individual protection | High quality product, shape, surface and surface chemistry tailored. | Use in collective air filters in shelters and vehicles for chemical warfare (Qian et al., 2020). Gas masks and respirators (Won-In et al., 2019, 2020). |
| | Nuclear energy | Radioactive isotopes | High quality product against sulphur, chlorine, dioxide ammonia, high surface area (microporous) | Passive capture filters impregnated with iodine (Suorsa et al., 2020; Deitz, 2021), decontamination of nuclear power stations ( El-Magied et al., 2017). Tailoring of chemistry can be adapted to relative humidity (Mahmoud et al., 2018). |
| | Air treatment | Industrial treatment<br>Environmental purification | Granular and shaped activated carbon. Microporous and surface treated. | Applications in conventional or hybrid filters. Control of acid gases (Borhan et al., 2015) and mercury removal (Sung et al., 2019; Sajjadi et al., 2018). |
| | Health | Personal protection, respiratory, apparel | Powdered and granulated activated carbon, high quality high surface area (microporous) | Treatment of drug overdose (Gao et al., 2018) and poisoning ( Bozorg et al., 2020). Filtration systems for water and air ( Macias-García et al., 2019) and purification of precursor materials (Fröhlich et al., 2019). |
| | Pharma | APIs<br>Cosmetics | Powder and granular with high quality. Microporous and surface treated. | Remove pollutants (Delgado et al., 2019), high COD removal ( Rocha et al., 2020). Drawing out toxins and remove impurities, skin care (Singh, 2021). |
| | Construction | Road construction | Microporous powdered activated carbon | Mercury tolerant materials, remove VOCs from asphalt (Zhou et al., 2020). |

by via patented technology with high-cost effectiveness (Liu et al., 2014). Some examples of the diverse uses and markets of biochar and activated carbons are listed in Table 1. The widespread use of activated carbon in so many large economic sectors result in a total market of several billion dollars per year, with a continuous worldwide growth rate higher than 10% (MarketWatch, 2021; Markets&Markets, 2021).

Despite the advantageous conditions for production of activated carbons from bio-wastes, most of the activated carbon used in Europe is imported. Indeed in SEE countries there are no producers of biochar (Nordic Biochar Network, 2021) and production of activated carbons using raw materials derived from fossil fuels cover less than 10% of the internal market. The possibility to implement sustainable production that involves valorization of bio-wastes to biochar while also transforming a fraction of this into activated carbon for the local markets, is an interesting combination of attractive business opportunity and environmentally friendly manufacturing.

This work presents the manufacturing route that a family-owned company located in Romania has developed to implement a circular economy vision, converting industrial and bio-wastes into a range of products. This work shows the necessary steps for an efficient production, describe the range and quantities of products and discuss the necessary steps to integrate energy saving in those operations.

## 2. Efficient production route for bio-wastes conversion to carbon-rich products

There are at least two possible ways to produce activated carbon from lignocellulosic materials: partial combustion or pyrolysis, followed by chemical or physical activation steps to increase microporosity and surface area (Salgado et al., 2018). Physical activation demand high temperatures and mild oxidant in the gas (water or $CO_2$) to open the porosity of the carbons. Using chemical activation, lower temperatures are used (for shorter times) due to the action of selected chemicals (i.e: phosphoric acid or sodium/potassium hydroxides or zinc chloride) for opening a porous structure (Tomczyk et al., 2020). When using partial combustion, the amount of activated carbon produced is proportional to the “burn-off” of the original material. The “burn-off” is the ratio between the weight of the initial material and the amount of activated carbon produced (Sajjadi et al., 2018).

If a pyrolysis process is used to generate biochar as an intermediate material, more chemical reactions take place and part of the carbon material is transformed to other products instead of being converted to carbon oxides. Although biochar is the main pyrolysis product, other volatile products and condensates are also recovered (Bhatt, 2014), making this process very attractive not only in terms of energy and recovered weight, but also to extend the range of valuable products obtained (Liang et al., 2021). The main constituents of wood are fiber, hemicelluloses, and lignin. These components are acknowledged to show a high multifaceted configuration in cell wall (Bledzki and Gassan, 1999). The proportion of fibers and lignin vary from one specie to the other and consequently, the ratio and properties of the different products will depend on the initial material used.

One of the possible ways to implement an advanced pyrolysis conversion is already in utilization in a family-owned company in Romania (Explocom GK). A scheme with the fundamental steps necessary for an efficient industrial production is shown in Fig. 1. A brief description of the steps follows:

1. Preparation of material: receive, store and prepare the biomass for drying.
2. Fill the retorts: biomass is placed in the reactors where the pre-drying process will be done
3. Pre-drying process: heat the reactor to a temperature between 70 and 110 °C for ~24 h.
4. Fill the pyrolysis furnace: place the retorts with dried input material in the pyrolysis furnace.
5. Pyrolysis process: the pyrolysis furnace is heated to a temperature varying between 450 and 850 °C for a period between 6 and 8 h. Heating is done by the recovered gases from previous retorts. Excess of combustible gases can be conducted to a CHP unit or used for other purposes.
6. Removal of retorts: empty the pyrolysis furnace using automated crane equipment.
7. Cooling the retorts: cooling down the retorts can be done by a forced chiller or by natural cooling. It is possible to recover significant amount of energy in this step.
8. Discharging: process that encompass the mechanical steps necessary to download the retorts.

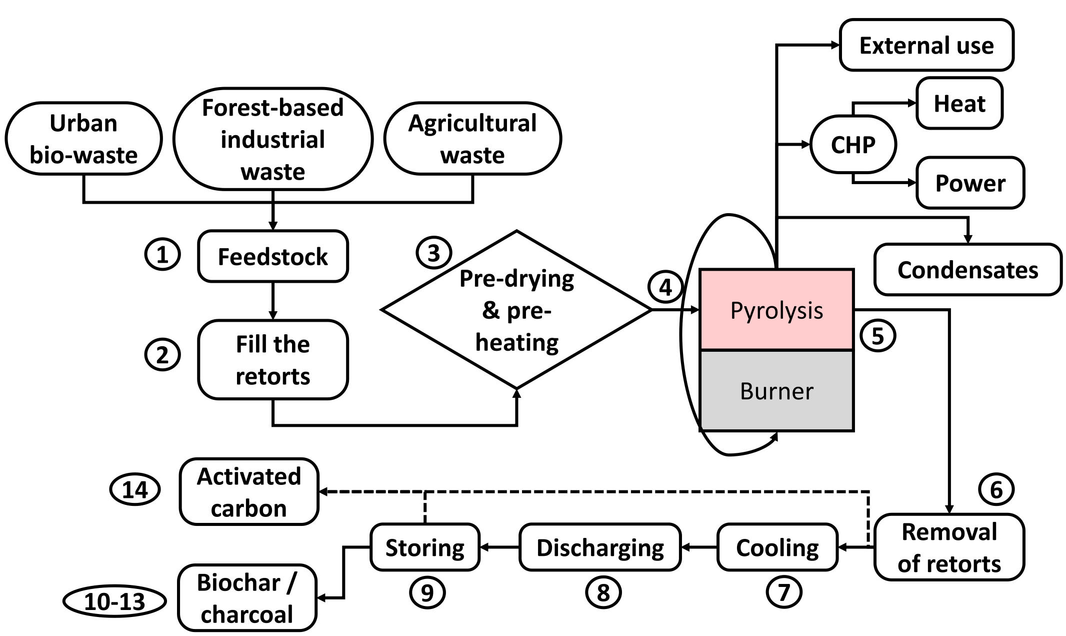


**Fig. 1.** Material flow of an industrial production of biochar/activated carbon by pyrolysis of sustainable raw materials also showing the additional products obtained from the pyrolysis process.

9. Storing: step where the biochar is stored or reintroduced in a vessel for biochar activation process. The activation process in this SME can be done by chemical process (wood vinegar penetration) or by heat treatment (hot water steam), according to proprietary technology (Geza, 2013).
10. Product upgrading and finishing: prepare the products according to specifics from the different end-costumers. The biochar and activated carbon products can be produced in different physical forms, such as granulated, powdered, pelletized or in form of briquettes or pills.
11. Packaging: pack the products for different markets according to preferences of the costumers while also complying with requirements from specific regulatory agencies.
12. Storage: Before commercialization, the product should be stored for a minimum period of one day and up to several months.
13. Transport and delivery to the costumers.
14. Activation of biochar to activated carbon: a part of the biochar is derived to be chemically activated. In terms of energy utilization, it is better that the material is extracted from step 6, but in case of need to cover market oscillations it can also be taken from steps 8 or 9.

The numbers in Fig. 1 represent the different steps of production described above. Note that steps 10–13 are predominantly of commercial nature and can vary depending on product needs. Steps 1–9 involve utilization of human resources, heavy machinery or energy utilization/integration. Step 14 (activation) should be tailored to meet the final product specifications.

The material flow presented in Fig. 1 shows the necessary steps to produce biochar and subsequently activated carbon. As mentioned before, one of the benefits from the pyrolysis process is that multiple products are obtained. The flow of other products extracted from the pyrolysis furnace is also shown in Fig. 1. These products can be categorized as:

1. Syngases, which are varying during the pyrolysis process, depending on temperature and other parameters ($CO_2$, CO, $CH_4$, $H_2$, Hydrocarbons, etc.)
2. Wood tar (with various constituents)
3. Wood vinegar: acetic acid, wood spirit, soluble tar
4. Biochar as final product or as a precursor to activated carbon
5. Ashes

The gaseous fuels can be valorized for heat and power generation, in a combined heat and power (CHP) plant. In most cases the produced heat is reutilized in pre-treatment (drying of input biomass materials) process, but it can also be used in local district heating system or to cover the energy demand of the facility. Additional heat can be obtained by implementation of heat recovery steps. The green power generated from the producer gases can be used in off-grid system or can be fed into the national power grid. Such action depends on specific cost assessment and must comply the local legislation and technical parameters.

Valuable byproducts can be obtained from the condensable fraction of the gas extracted from the pyrolysis furnace. These additional products increase the weight efficiency of this approach for manufacturing carbon-rich materials. The condensate is an aqueous mixture of pyroligneous acids and wood tar. At the scale of industrial production there is possibility to produce pyroligneous acids, wood oils, wood tar, and alcohols in a recoverable manner. In most cases, the main customers of these products are the chemical and fuel industries. A summary of the markets and economy sectors from the additional products obtained by the pyrolysis process are given in Table 2.

## 3. Product distribution at industrial scale

The concepts shown have already been implemented in a small-medium enterprise (SME) in Romania. Explocom GK is a private, family-owned company in Romania that is producing charcoal, biochar and other derived products. The company developed its own patented using the cascading approach shown in Fig. 1. Their production capacity is currently being upgraded for accepting approximately 112.000 tons of raw material per year, in up to 48 retorts.

The process starts with the preparation of the input material, namely with pre-drying of the solid biomass achieving 15–20% moisture content in a dedicated and specialized facility installed for this purpose. To prepare 100.000 atro-tonne input material, it is necessary to have at least 25% more available raw material due to water losses. “Atro-tonne” is a unit that denotes one ton of the dry material (wood/logwood) at zero moisture content. Under regular conditions, the solid biomass materials can have 40–50%–15% moisture content, depending on their origin. Fresh wood by-products from sawn-mills, logging process etc. have the higher moisture content (up to 50%), while straw, corn stalk, corn cob, sunflower husks after harvesting, or in other cases in agriculture have a smaller moisture content (18%).

In the production flow, around 22% of the total raw material becomes biochar. If all the biochar is transformed into activated carbon, the weight of the final product will decrease to less than 20% or less, depending on the desired final properties of the product.

At the temperature of the pyrolysis furnace, many products are obtained as gases. If those gases are condensed, two types of products can be separated. The volatile products after condensation (producer gases) are going to be valorized as synthesis gases for CHP or for a boiler, producing heat and power. For every ton of pyrolysis feedstock, 200 kg of syngases are produced containing approximately 600 kW of thermal energy. This gas is recycled in the plant to avoid using fossil fuels like natural gas (or additional wood) for heating the retorts. Regarding energy utilization, the input of external energy used for the production is around 150 kW for every ton of biochar produced. Only 10% of this

**Table 2**
Specific markets, applications and benefits of other products obtained from pyrolysis of biomass when producing biochar.

| Product | Market Sectors | Sub-Sectors | Product grade | Main Benefits |
|---|---|---|---|---|
| **Wood Vinegar** | Agriculture | Pesticide production | Organic Fertilizer and Pesticide | Organic fertilizer and pesticide |
| | Chemistry industry | Paint and Coating industry | Sub-component | Bio-based component |
| | Food Industry | Meat Production | Sub-component | Ingredients |
| | Activated Carbon production | Activated Carbon production | Sub-component | Chemical process in activation of carbons |
| **Crude Alcohol** | Biofuel production: Bioethanol | Ethanol production | Sub-component | Raw material/constituent fluid |
| | Chemistry | Various sub-sectors | Sub-component | Raw material/constituent fluid |
| **Wood Vinegar** | Marine application | Ship construction and rope production | | Organic caulking and insulation material |
| | Construction | Wooden house sector | Main component | Organic caulking and insulation material |
| | Furniture Industry | Furniture sector | Main component | Organic caulking and insulation material |
| **Wood Tar Oil** | Chemistry | Bio-based Industry | Sub-component | Organic material |
| | Cosmetics | Organic beauty industry | Sub-component | Organic material |
| | Construction | Building Restoration and Maintenance | Main component | Organic caulking and insulation material |
| | Furniture Industry | Furniture Restoration and Maintenance | Main component | Organic caulking and insulation material |
| | Health & Pharma | Pills and Therapy | Sub-component | Organic material |

energy is used in the pyrolysis reactor, to lift and put town the retorts and the rest of the energy is for the rest of the operations like biochar granulation, briquetting, etc. In the eventuality that more thermal energy is required for pre-drying and pre-heating, a fraction of the produced ethanol and crude vinegar can be used.

The condensates, such as heavy tar and distillate, will be later divided into oils and acid water. The other branch of condensates become pyroligneous acids, wood vinegar, alcohol after distillation and acetate liquor after evaporation and drying. The production flow is presented in Fig. 2.

## 4. Environmental and economic benefits of the existing production route

The process of production of biochar, activated carbon and additional bio-products presented here has multiple advantages. From the environmental point of view, this process can valorize agriculture bio-based products and bio-wastes from forest-based industries. According to Ahmed (2016), the main drivers to become a considerable input feedstock in activated carbon production are: availability for extended periods and available volumes, proximity, price, transportation, cleanliness and homogeneity of the raw material (Anwar et al., 2014). The geographical location of the company, close to the Eastern Carpathian Mountains in Romania is a fundamental advantage because there are large volumes of by-products from forest-based factories; a large majority of the raw material (wood wastes, corncob, straw, etc.) comes from locations <100 km.

The wide availability and the environmentally friendly nature of the resources used are also important incentives (Bhat et al., 2020). It is also worth to mention that the Joint Research Center of the European Commission stated that the greater part of the biomass from wood area collected in the EU countries is demeaning natural environments and wrecking the climate goals (Camia et al., 2020). Harvesting wood only for bioenergy production is no longer considered as renewable energy and such practice is undermining the greenhouse gas reduction goals. Indeed, wood harvesting for production of bioenergy will probably reduce the European carbon stocks and necessitate supplementary remedial activities to mitigate emissions in other economic segments to achieve climate targets (Frietsche et al., 2020).

This approach offers many profitable business opportunities. The biochar offers several benefits for agriculture sector, the original source of the raw material, making this approach entirely circular and sustainable. The main benefits of biochar products are: improvement on soil permeability and porosity, increase the water retention capacities, reduce soil erosions, stabilize and limit the soil contamination, support the micro-organisms and accelerate the humus formation process. The better soil structure will have the capabilities for water absorption and for an increased water storage (Ding et al., 2016), although some reports indicate lack of evidence for such enhanced properties (Holt et al., 2020).

Biochar products can be used as bio-fertilizers for soil upgrading, reducing the demand of synthetic fertilizers and at the same time acting as $CO_2$ sequestration materials (Won-In et al., 2020). Agricultural fertilizers used in disproportionate manners can act as polluters, significantly enhancing the eutrophication process at water reservoirs means heavy issues in many places due to lack of water treatment or inadequate water treatment processes (Wimalawansa and Wimalawansa, 2015).

Together with the environmental benefits, the valorization of the biomass waste materials into valuable and sustainable products, also contributes to support a local economy, particularly regarding the generation of new jobs in rural areas (Stegman et al., 2020). An important economic benefit is that the waste from above-mentioned streams can be considered as feedstock and can render additional income for the farmers (Yahya et al., 2018) for applications that they may have close to their facilities like dye removal applications (Hammeed and Daud, 2008).

While the presented approach highlights the production of biochar, there are important economic considerations to be made about this production route. While biochar can have a market price of 350–500 EUR/ton (Holt et al., 2020), the other liquid products have a higher market price: i.e. wood tar & ethanol ~1000 EUR/ton. Since their overall production in weight is much higher than charcoal, the bulk income in sales comes from marketing the entire set of products.

For cases of market need and mostly because of the energy efficiency achieved in this plant where there is available syngas, one possibility is to upgrade biochar to activated carbon. The market price of activated carbon is wide, depending on the final market. For drinking water purification, the market price is ~1200 EUR/ton while in applications like pharma industry, it can reach up to 10000 EUR/ton. If a high quality product can be produced with available energy, the profitability can be over 15%.

## 5. Product quality control and commercial driven approach

The circular bio-economy approach given above will not be industrially interesting if the products do not have a verifiable high quality. The European Biochar Certificate (EBC) has been elaborated to act as a tool to verify reliable quality standards for such products. Currently, the

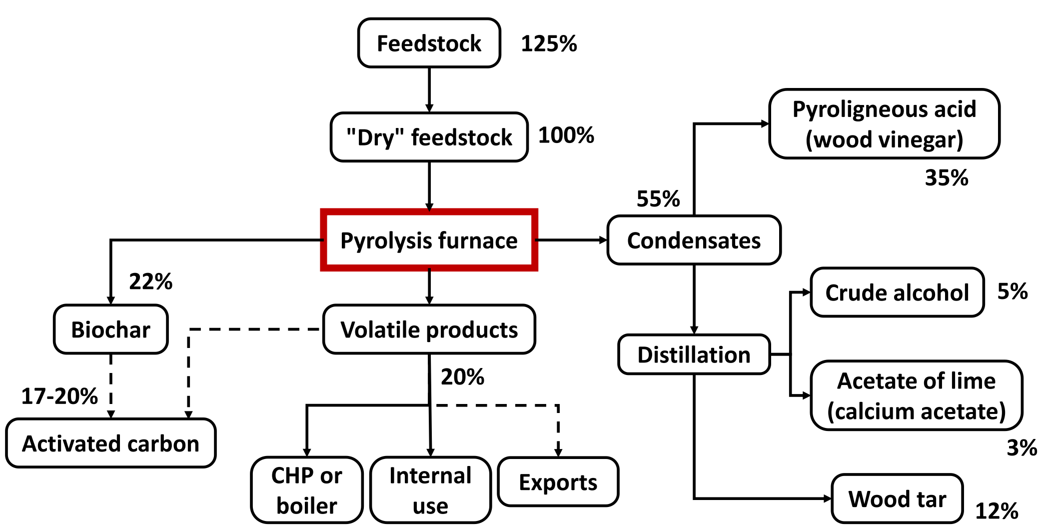


**Fig. 2.** Flowchart and product distribution of a pyrolysis process for production of sustainable activated carbon and bio-based products.

(The European Biochar Certificate, 2021) is a voluntary manufacturing norm in Europe.

EBC standards are set at different levels, aiming to increase the quality level (up to the best of scientific knowledge) and to support the professionals and biochar producers to prevent any danger from health and environment point of views under the utilization of biochar products (The European Biochar Certificate, 2021). The Ithaka Institute from Switzerland issued guidelines to establish an evaluation instrument based on the newest scientific results and practical experiences which are accepted within EU and EEA countries, respecting the EU fertilizer regulations or carbon-sink regulations published in EU Circular Economy Package (European Comm., 2021).

The aim of these guiding principles is to provide the basis and guarantee the control of biochar manufacturing processes and excellence on investigated, with authorization, economically feasible and practically valid methods. End-consumers of activated carbon with the ECB can benefit from clear and confirmable checking and quality guarantee.

The results for different materials performed at Eurofins laboratory (Germany) resulted in the DIN EN ISO/IEC 17025:2005 certificate under the DAakks German Accreditation System for Testing (Eurofins, 2020). The analyses are reported as supplementary information and report properties on structural and textural properties of the samples tested as well as the presence of metals, salts and organic molecules. Two products from Explocom GK (activated biochar and wood vinegar) have received in 2019 the European Biochar Certificate (Annex 5) from European Chemicals Agency ECHA. Those certifications validate the quality of the products obtained with processes applying principles of circular bio-economy. The results of the products from Eurofins laboratory and the Biochar certificate are presented in the Supplementary Information.

This communication wants to highlight the pathway that a family-owned company has taken to turn its operation profitable and sustainable at the same time. Important steps for improving the operation of the plant in terms of sustainability are:

- Modernize all steps that are critical to energy consumption.
- Develop a smart system for syngas management and storage
- Use automatic equipment in critical operations will improve reliability and also energy integration.

Using the approach presented in this work, the local company (Explocom GK) was able to create up to 50 direct jobs for local families, and also resulting in 20 indirect jobs at the regional level. At the heart of the successful implementation of environmentally friendly processes is just the same way of thinking that drove successful stories of manufacturing before: strong knowledge of the processes that lead to possession of own technology and a clear vision of the desired pathway in middle and long term. The "only" difference with a traditional success story is that when sustainability is involved in the long-term goals, the environment is a clear winner. Indeed, there are plenty of possibilities to implement concepts of circular bio-economy to transform diverse markets into sustainable production with adequate quality and profitable margins.

## 6. Conclusions

Activated carbon and biochar are important products that serves several sectors of our economy. A sustainable production of these carbon-rich materials can contribute to reduce emissions of carbon dioxide. If the source materials are from industrial wastes of agriculture and the products are used for agricultural purposes, a bull bio-circularity principle is possible.

A clear methodology for industrial production of biochar and activated carbon via pyrolysis of agricultural and forest-based industrial wastes has been presented. This methodology can produce biochar as main product and also render a comprehensive set of "by-products" like wood vinegar, alcohol, acetate of lime and wood tar. The efficient energy integration in the plant allows recycling of syngases to heat the pyrolysis reactor avoiding use of fossil fuels or external raw materials and can also provide energy to convert part of the biochar into activated carbon, enhancing the profitability of the plant.

This route does not only use sustainable materials as a starting point, but it also expands the weight profitability of the process and converts the carbon in the source material into valuable products. The methodology presented and the product distribution for industrial production is being performed at the scale of 100 kt of incoming material processed per year.

Based on market demand, a significant increase activated carbon production is expected. The route shown here demonstrates that if this commodity is produced using forest residues, a sustainable manufacturing is possible. New energy-efficient machines and equipment with heat integration for this sector can contribute in achieving further increase in energy efficiency.

The present manufacturing practice case shown here is an example of how to deploy circular bio-economy principles at industrial level while at the same time creating and activating local and regional supply value chains. To multiply such sustainable practice examples, a strategic deployment agenda is needed for local and regional entities. Since the resource-emitting areas for bioeconomy developments and production activities are the forest-reach regions, rural and coastal areas, it is possible that specific regions will experience social and economic renaissance.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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